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Glass Science and Technology 6

The Manufacturing Technology of Continuous Glass Fibres

Third, completely revised edition

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and, for reasons of purity, are often manufactured in furnaces lined with platinu alloys, the quality requirements of glass for the drawing of continuous fibres a significantly higher since 'sorting' of good glass from bad is inherently impossib in glass fibre manufacture.

The problem of achieving the necessary quality standard is linked to a prop choice of raw materials for glassmaking, the proper selection and placing of refra tories in the glass melting furnace and the proper control of the glassmaking an subsequent conditioning processes.

The growth of the glass fibre industry since 1945 and the comparative price st bility of glass fibre products since the 1970's are linked directly to improvements i glass quality over that period brought about by the development of refractories better performance, higher melting temperatures, longer furnace life, better unde standing and control over parameters affecting productivity and quality, improve control instrumentation and computerisation of processes, as well as the larger scal of operations resulting from greater confidence and experience. Thus, in the 1950 the first direct-melt furnace had a production capability of 3 U.S. tons per da and the furnace life was 9 months. In 1966 the biggest direct-melt furnace had capacity of 10 U.S. tons per day. By 1970 furnace life had extended to 4 year single furnaces of less than 15 U.S. tons per day were becoming uneconomic an furnaces of 40 U.S. tons per day, and over, were being successfully operated. Th largest furnaces currently in operation (1992) are believed to have a rated outpu of about 200 U.S. tons (180 metric tons) per day.

4.2. Glass compositions

Over 99% of all continuous glass fibre produced is of a composition referred to a 'E glass'. Although E glass was originally developed for electrical applications, an there is a growing market for E glass in electrical applications, the use of E glas has spread into many other applications where the properties of the fibre as suc were found to meet the requirements. E glass therefore dominates the world marke for reinforcing fibre; in cases where glasses of different compositions are used, ther is a specific reason for this, not the other way round. The composition of E glass i best given in terms of ranges of its constituents (table 4.1).

Up to 20 years ago, fair quantities of fibre were also being made from soda-lime silica glass of sheet composition, called 'A glass' in the industry. This was attractiv for producers during the period when patents covering E glass prevented them fro using it, and/or when a local source of cheap sheet glass scrap was available; it wa never, to the best of the author's knowledge, set up as a direct-melt process bu was always produced by the remelt process. As a proportion of the total world fibr production it is now insignificant, although for many general purpose composite A glass fibre reinforcement has been shown to be perfectly adequate and, on a equivalent scale, should be cheaper to produce than E glass.

E glass has one particular disadvantage: it is easily dissolved in dilute mineral

Table 4.1
The composition of E glass, the most important composition for the formation of glass fibres [1].

Constituent	Weight %
SiO_2	52–56
Al_2O_3	12–16
B_2O_3	5–10
TiO_2	0–1.5
MgO	0–5
CaO	16–25
Na_2O+K_2O	0–2
Fe_2O_3	0–0.8
F_2	0–1

acids. For this reason a chemically resistant glass, called C glass, is used in the form of fibre for composites which will be in contact with, or will be containers for, acidic materials, e.g. tanks in the electroplating industry.

C glass is, in theory, also cheaper to produce than E glass. As a result, where production volumes warrant it, C glass is also used as an alternative to E glass in the manufacture of roofing mat for the reinforcement of bitumen. In practice, since the volume of E glass manufactured for this purpose exceeds that of C glass by far it competes successfully with it due to the scale of manufacturing operations and the high degree of mechanisation which has been achieved.

Two special glasses are used in applications where composites of highest mechanical performance are required. They are S glass[1] (manufactured by Owens Corning Fibreglass Corporation) and R glass (manufactured by Vetrotex). These glasses are similar in composition (see table 4.2), are difficult and costly to make and their use is therefore limited to sophisticated applications in the fields of aircraft and engine construction, missiles and specialised sports equipment.

Typical compositions of E glass [1] and of the other glasses mentioned together with some of their basic properties are given in table 4.2.

Cemfil [2] and AR [3] glasses are two glass compositions used for the reinforcement of cement; the amounts manufactured for this purpose probably do not exceed 20 000 tons/year. They are very small when compared to E glass; however, this type of fibre reinforces 20–30 times its own weight of cement.

With the growth of the computer and associated industries, glasses of dielectric constant lower than that of E glass have been developed in order to provide glasses of lower dielectric constant and faster response time of composite printed circuit boards. Examples from Japan [4], the United States and Europe are given in table 4.3.

[1] 'S glass' is a registered trade name.

Table 4.2
Composition in weight % of glasses used in fibre manufacture and some of their properties in fibre form.

Constituent or property	E glass	C glass	A glass	S glass	R glass	Cemfil glass[2]	AR glass[3]
SiO_2	55.2	65	71.8	65.0	60	71	60.7
Al_2O_3	14.8	4	1.0	25.0	25	1	–
B_2O_3	7.3	5	–	–	–	–	–
ZrO_2	–	–	–	–	–	16	21.5
MgO	3.3	3	3.8	10.0	6	–	–
CaO	18.7	14	8.8	–	9	–	–
Na_2O	0.3	8.5	13.6	–	–	11	14.5
K_2O	0.2	–	0.6	–	–	–	2.0
Li_2O	–	–	–	–	–	–	1.3
Fe_2O_3	0.3	0.3	0.5	tr.	–	tr.	tr.
F_2	0.3	–	–	–	–	–	–
Liquidus temp. °C[a]	1140		1010			1201	1172
Fiberising temp. °C[b]	1200		1280			1470	1290
Tensile strength of single fibre at 25°C, kg/mm^2	370	337	310	468	449	292	
Density, g/cm^3	2.53	2.49	2.46	2.48	2.55		
Refractive index n_D	1.550		1.541	1.523			
Coefficient of linear thermal expansion per $°C \times 10^6$	5.0	7.1	9	2.85	4.10		
Volume resistivity in Ω cm	10^{15}		10^{10}	10^{16}			
Dielectric constant at 25°C and 10^{10} Hz	6.11				6.2[c]	5.21	
Loss tangent at 25°C and 10^{10} Hz $\times 10^3$	3.9				1.5[c]	6.8	
Na_2O loss/h/g in water at 100°C, μg	112		274				

[a] The liquidus temperature is the highest temperature at which a glass, if held there sufficiently long, will develop crystals. The greater the difference between this and fiberising temperature, the more stable the fibre forming process.
[b] Indicates temperature at which the viscosity of the glass is 10^3 poises.
[c] Measured at 10^6 Hz.

E glass dominates the continuous glass fibre market. As is evident from table 1, it does not have a defined composition, but is a glass of defined electrical properties. Since these are governed by the alkali content of the glass, E glass is usually defined in national and international specifications in terms of the alkali content of the glass, i.e. that the glass should not have an alkali content when calculated as Na_2O exceeding 1% by mass. (Japanese standards limit the alkali content to 0.8% as Na_2O.)

Table 4.3
D glass compositions in weight % ('D' stands for 'dielectric').

Composition/properties	Japan[4]	USA	Europe[a]
SiO_2	45–65	75.5	72–75
Al_2O_3	9–20	0.5	–
B_2O_3	13–30	20.0	20–23
CaO	–	0.5	–
MgO	–	0.5	–
CaO+MgO+ZnO	4–10	–	–
$Li_2O+Na_2O+K_2O$	0–5	3.0	max. 1
Miscellaneous	–	–	max. 4
Dielectric constant at 10^{10} Hz	4.3–4.9	3.8	3.85
Loss tangent at $10^{10}\text{Hz}\times 10^3$	–	–	0.5

[a] Manufactured by Vetrotex.

Basically, E glass is a calcium alumino-borosilicate glass containing less than 1% of alkali oxide when calculated as Na_2O. The actual alkali oxide content, as well as the presence of other trace elements, are usually governed by the choice of raw materials which, for cost reasons, should be natural materials whenever possible. Most glasses contain small but important quantities of fluoride added to assist the dissolution of raw materials and lower the liquidus temperature of the glass. Some glasses also contain deliberate substitutions of MgO for CaO.

It might be thought that the composition of E glass is, after over 50 years of its existence, now an established composition varying only as a result of variations in locally-available materials; but this is not so. Several factors encourage and/or force manufacturers to re-examine the composition of E glass, namely the need to reduce atmospheric pollution due to gases and dust discharged from E glass furnaces, production problems and cost of raw materials, especially of B_2O_3-containing materials. table 4.4 shows a range of E glass compositions including fluoride-free and fluoride-and-boric-oxide-free versions. In this group the glass in column 6 is of particular interest since its development involved a careful study of the benefits or otherwise of the presence of MgO; it concluded that, at about 1.8% MgO, the liquidus temperature[2] was at a minimum (1083°C) and the fibre forming temperature was also lower than with traditional E glass (1212°C).

Of the minor constituents, it is worth noting that the presence of small quantities of fluoride assist melting of the glass, contribute to a reduction in the liquidus tem-

[2] The liquidus temperature is the highest temperature at which a glass, if held there sufficiently long, will develop crystals. For reasons already stated, the presence of even submicroscopic crystals is disastrous for fibre manufacture. The lower the liquidus temperature, and the greater the difference between liquidus and fiberising temperature, the more stable the composition as a glass.

Table 4.4
E glass compositions 1940–1990 (weight %).

	1 original E glass [6]	2 'improved' E glass [7]	3 621 glass [8]	4 MgO-free glass	5 816 glass [9]	6 F-free glass [10]	7 B&F-free glass [11]	8 low glas [12]
SiO_2	60	54.0	54.0	54.3	58.0	55.3	59	55.8
Al_2O_3	9	14.0	14.0	15.1	11.0	13.9	12.1	14.8
B_2O_3	–	10.0	10.0	7.4	–	6.8	–	5.2
TiO_2	–	–	–	–	2.4	0.2	1.5	–
MgO	4	4.5	–	0.1	2.6	1.8	3.4	–
CaO	27	17.5	22.0	22.1	22.5	21.4	22.6	21.0
ZnO	–	–	–	–	2.6	–	–	–
R_2O[a]	–	1.0	1.0	0.4	1.0	0.4	0.9	1.4[b]
Fe_2O_3	–	trace	trace	0.2	0.1	0.2	0.2	n.d.
F_2	–	0.5[c]	0.5[c]	0.6	0.01	–	–	0.5

[a] Total of alkali oxides.
[b] Note alkali content (reported as Na_2O) above 1.0%.
[c] Estimated from statement in patents that 'fluorspar may be substituted in amounts of 1 for part of the boron oxide ...'.

perature and ease fibre formation. The presence of iron oxide also has a signifi influence on the stability of the fibre forming operation due to the fact that presence increases the rate of infra-red emission, i.e. the rate at which heat is from the glass as it leaves the nozzles of a bushing.

In the last 20 years, increased consideration of environmental effects has le legally enforceable restrictions on permitted pollution levels resulting from in trial activities. This is now of such importance that a more detailed discussion the current situation is called for (see Section 4.5.9). The causes of atmospheric lution originating in the glass composition and melting operation for a partic E glass composition are:

- fluoride vapours, probably in the form of fluorosilicic acid, H_2SiF_6, hydroflu acid, HF, and fluoborates;
- sulphur oxides, from sulphur in the oil used for combustion plus a trace of sulph in the raw materials;
- nitrogen oxides, resulting from the oxidation of nitrogen in the air;
- batch dust carried over from the melting chamber and into the atmosphere;
- boric oxide, as vapour from the furnace which condenses to a smoke on cooli

The manufacturer, when faced with this problem, has certain technical cho which can minimise pollution. He has a limited choice of composition and a ch of furnace (electric heating within the glass eliminates pollution by sulphur nitrogen oxides and reduces losses of B_2O_3, fluoride, and dust – see Section 4.5.8 He may also have a choice of fuel which can minimise the formation of sulp

oxides, and he can now deal with nitrogen oxide pollution by installing a firing system which avoids them being formed. If he cannot control pollution by these means he has to rely on treating the polluted waste gases to reduce all pollutants to acceptable levels before discharge to the atmosphere. A more detailed discussion of pollution control is given in Section 4.5.9. In the glass industry in general, dust has been significantly reduced, melting rates increased and the quality of the glass improved by pelletising the batch [5]. So far, at least, the glass fibre industry does not appear to have followed this example.

To consider a change in glass composition is a very serious undertaking since it involves changes to a large number of parameters all of which have been, up to then, considered as an established part of an integrated production process. Many problems are likely to surface downstream in the production line and all unexplained faults will tend to make the suitability of the new glass composition suspect. Despite these problems, economic pressures and pollution regulations, the high cost of some materials and a better understanding of the factors interlinking glass composition with process engineering and the properties of glass fibres has given some manufacturers sufficient courage to experiment with and undertake changes in the composition of E glass.

Consideration of these compositions might as well include a look at how E glass developed between 1940 and 1990. Table 4.4 gives seven examples. Composition 1 is that of the original E glass which resulted from very careful work to find a substantially alkali-free glass that could be manufactured at the then practical founding temperatures and using available refractories [6]. This was improved by Composition 2; in it, the addition of fluorspar as a partial replacement for B_2O_3 was suggested to help melting and reduce the liquidus temperature [7]. This glass suffered from the fact that, although the melting temperature was, by present standards, very low, the then available refractories, namely pressed zircon, dissolved in the glass very rapidly. This not only gave very short furnace campaigns, but the dissolution of zircon in the glass raised its liquidus temperature, thus increasing the risk of the glass devitrifying before or during fibre forming. This problem was attacked in Composition 3, known as '621' glass [8]. The major change was the elimination of MgO and corresponding increase in CaO content. The liquidus temperature of 621 glass was lower than that of the 'improved' E glass, and was thus able to accommodate the addition of ZrO_2 from refractories without such a high risk of devitrification. Composition 4 is a variant 621 glass in which the B_2O_3 content has been reduced.

With improved and new refractories, especially the development of isostatically-pressed chrome and zircon refractories, the rate of corrosion of refractories decreased to such an extent that melting temperatures could be increased to nearly 1600°C and furnace campaigns extended. Nevertheless, the two types of E glass composition, i.e. with and without MgO as a significant constituent have remained in use. With increasing founding temperatures, B_2O_3 could be reduced. Both types contain fluorides at about 0.4% F_2.

As laws governing pollution came into force some manufacturers tackled the

problem of fluoride emissions by developing glasses which were free of deliberat additions of fluoride, i.e. the only fluoride still found was due to trace amoun present in, for example, the clay (used as source of alumina). It was also found a this stage that the presence of even very small amounts of fluoride, i.e. 0.01% F significantly assisted fibre forming; the effect is as if a trace of fluoride increase the surface tension between glass and the platinum alloy of the nozzles of th bushing for fibre forming, thus helping to stabilise the fibre forming process (se also Section 5.2.1).

Having started on the elimination of fluoride pollution by means of compositio changes, attention was also drawn to the smoke of condensed B_2O_3 which is dis charged from furnace chimneys. The losses are very considerable since, in a norma gas or oil-fired tank furnace, about 10–20% of the boric oxide added in one form o another is lost into the atmosphere. Since B_2O_3 is the most expensive raw materia being used – it accounts for about one half of the raw materials costs – and has, o occasions, been in short supply, the concept of eliminating all problems by avoid ing the raw materials which caused them was inviting. This led to Composition 5 known as '816' glass [9]. It is worth noting, however, that raw material costs wer not reduced and the process details had to be adjusted to accommodate the highe liquidus temperature of this glass.

Composition 6 is a fluoride-free B_2O_3-containing E glass of a type used in Japa for many years, although this particular composition is a recent improvement o this type [10].

Composition 7 is an American E glass free of both fluoride and boric oxide differing only slightly in composition from 816 glass [11]. It is not clear to wha extent these two glasses are in large-scale use. Most manufacturers have preferre to use established E glass formulations and to install pollution control equipmen while continuing their efforts at minimising the evolution of contaminants; in thi connection the contribution of electric melting is significant (see Sections 4.5.8.1 and 2). Also, some of the pollution equipment itself permits all or part of th pollutants to be recycled back into the glassmaking process (see Section 4.5.9).

Composition 8 is (almost) an E glass specially formulated to possess a low re fractive index for its use in translucent sheeting [12]. Although its alkali conten of 1.4% as Na_2O takes it outside the limits for E glass proper (1.0% Na_2O max.) there is no reason why it should not be used for non-electrical applications.

4.3. Selection of raw materials for E glass manufacture

The selection of raw materials must be based on composition, reliability of quality and supply, and cost. Natural materials usually contain sometimes major, sometimes minor proportions of oxides which are not the main constituents for which the raw material in question is being used. The presence of minor constituents must be checked carefully, e.g. of alkali and iron oxides, so that certain permissible maxima in the glass composition are not exceeded.

Table 4.5
Comparision of particle sizes in micrometers compared to U.S.A. and British Standard Sieve equivalents.

U.S.A. standard sieve	micro-meters	British standard sieve
275	53	300
213	75	240
141	100	156
99	150	100
70	210	72
60	250	61

A major difference between usual raw materials and raw materials for E glass is that the raw materials must be finely powdered; if they are not, silica and other materials of low solubility will separate out on top of the melt as a scum.

With the exception of raw materials for introducing boric oxide, most other raw materials should be available within reasonably short distances. When considering transport costs to the plant, bulk shipments usually reduce the costs considerably.

4.3.1. Raw material for introducing silica (SiO_2)

Glassmaking sand finely powdered but not of the lowest iron content used in the glass industry is suitable. A typical analysis is:

SiO_2	98.05%	min.
Al_2O_3	0.85	
Na_2O	0.1	
K_2O	0.4	
Fe_2O_3	0.1	
H_2O	0.1	

A typical particle size distribution is:

coarser than 150 μm	0.1%
between 150 and 75 μm	0.8%
between 75 and 45 μm	6.0%
finer than 50 μm	remainder

For a comparison of micrometer and mesh sizes, see table 4.5.

4.3.2. Raw materials for introducing alumina (Al_2O_3)

(1) The preferred materials is a china clay of low alkali and iron contents. A typical specification would be:

SiO_2	44%	
Al_2O_3	37	
CaO	0.6	
Na_2O	2.0	max.
Fe_2O_3	1.0	max.
Water	1.0	max.

The clay should be supplied as a very fine powder, nominally 50 μm with t following particle size distribution:

coarser than 150 μm	1%	max.
between 150 and 75 μm	1%	max.
between 75 and 50 μm	99%	

(2) In the event that a suitable clay is not available, synthetic alumina in hydrate or calcined form can be used. These materials, however, will prove to be mo costly than clay. The maximum particle size for the hydrated and calcined form should be 75 μm or 45 μm respectively.
While glass makers prefer the use of hydrated alumina for reasons of easi incorporation of Al_2O_3 into the glass, this material does evolve considerabl quantities of steam (67% of the weight introduced) which increases the loss B_2O_3 and dust in fuel-fired tank furnaces, and greatly increases evolution dust in cold-top electric furnaces.

(3) Other alumina-containing natural materials can be used provided they permi the formulation of a mixture which results in E glass within the permitte tolerances. All these materials must meet the particle size characteristics of th clay given above.

(4) Clays are found either as high silica/low alumina or high alumina/low silic clays. If the manufacturer is fortunate enough to have access to both type of cla of acceptable quality, then he should use both in proportions that would mak the use of silica unnecessary. This will result in easier glass melting condition which will permit a reduction in furnace temperature or increased melting rat out of a furnace of given dimensions.

4.3.3. Raw materials for introducing boric oxide (B_2O_3)

An allowance of about 20% may have to be made for loss of B_2O_3 in fuel-fired tank furnaces.

(1) From the point of view of cost, natural calcium borate, called colemanite, and originating mainly from Turkey, is preferred outside North America. It is cheaper in terms of B_2O_3 introduced, results in lower losses of B_2O_3 during melting when compared to boric acid, but suffers from the fault of most natural materials, only in this case more than most, namely, that the composition is not consistent and materials from different locations not only vary in B_2O_3 content but can also contain deleterious impurities. However, responsible im-

Table 4.6
Typical grades of colemanite suitable for use in the manufacture of glass for fibre formation.

Constituents	A250	B250
SiO_2	4.0	5.0
Al_2O_3	0.5	0.5
B_2O_3	42.0	40.0
MgO	2.0	3.0
CaO	27.0	29.0
Fe_2O_3 max.	0.1	0.1
Na_2O+K_2O	0.25	0.3
LOI at 850°C	22.0	22.0

porters have set up facilities for grading, crushing and blending colemanite ores from selected sources so that consistent grades of colemanite of declared B_2O_3 content can now be obtained which are free of objectionable impurities such as chromite, arsenic, niccolite (NiAs) and arsenical pyrites.

Typical grades of colemanite now available with their typical analyses are given in table 4.6. The particle size analysis for both grades is:

coarser than 250 μm	5%	max.
between 250 and 125 μm	15%	
between 125 and 63 μm	35%	
finer than 63 μm	remainder	

(2) In North America colemanite and boric acid, H_3BO_3, or boric oxide (usually referred to as anhydrous boric acid) are used. The last two materials are available at very high purity and in granular form. Particle size should be under 150 μm.

The losses occurring during glass melting in fuel-fired tank furnaces are likely to be considerable; they can range from 15 to 25% of the B_2O_3 added to the batch mixture. The actual rate of loss varies with the melting conditions, including the rate of E glass production. This loss must be allowed for when calculating the batch formulation.

4.3.4. Raw materials for introducing magnesia (MgO)

(1) If available, a convenient material is dolomite, an equimolecular magnesium/calcium carbonate; its use introduces 1.5 times its weight of CaO. A typical composition is:

MgO	20%	
CaO	31	
SiO_2	1.0	max.
Al_2O_3	0.6	max.
Na_2O	0.4	max.
K_2O	0.2	max.
Fe_2O_3	0.4	max.

The particle size is nominally under 150 μm. A typical specification would be:

coarser than 150 μm	2.0%	
between 150 and 75 μm	56.0%	max.
between 75 and 50 μm	40.0%	max.

Although often used, dolomite, when fed into a furnace as part of a mixture of raw materials, decrepitates, thereby giving rise to dust which corrodes furnace refractories and is carried into the atmosphere. For this reason some manufacturers have chosen to use the '621' type of E glass composition (see table 4.4).

(2) The alternative material available in North America is burnt dolomite (MgO·CaO). It does not decrepitate. A typical composition is:

SiO_2	0.2%
Al_2O_3	0.2
CaO	56.8
MgO	41.0
Fe_2O_3	0.11
SO_3	0.78
H_2O	0.11

In the absence of the above forms of dolomite, other magnesia-containing minerals can be used provided their contribution to the total batch composition fits into the overall composition of the E glass targeted; such minerals could be olivine, or magnesite (magnesium carbonate).

4.3.5. Raw material for introducing calcium oxide (CaO)

Universally available limestone or calcite is used. A typical specification would be:

CaO	55.4%	min.
Al_2O_3	0.2	max.
P_2O_5	0.1	max.
MnO_2	0.1	max.
Fe_2O_3	0.05	max.
H_2O	0.4	max.
S	0.1	max.

The particle size distribution, nominally finer than 150 μm, should be:

coarser than 150 μm	2.0%	max.
between 150 and 75 μm	28.0%	max.
between 75 and 50 μm	70.0%	min.

4.3.6. Raw materials for introducing fluoride (F_2)

The most common raw material used is fluorspar, a natural calcium fluoride:

F_2	47.3	
CaO	70.2	
SiO_2	1.0	max.
Al_2O_3	1.0	max.
Fe_2O_3	0.25	max.
PbO	0.2	max.
Water	0.4	max.

An acceptable particle size distribution could be:

coarser than 400 μm	nil	
between 400 and 150 μm	4%	max.
between 150 and 50 μm	41%	
finer than 50 μm	remainder	

In calculating the quantity of fluorspar required, it is necessary to allow for the fluoride losses. In fuel-fired tank furnaces these will be about one half of the F_2 added; in cold-top electric furnaces about one quarter. It is evolved probably as H_2SiF_6, and the SiO_2 thus lost must be allowed for in the calculation by replacing it. Note that no CaO is lost: it ends up as CaO in the glass.

4.3.7. Use of sodium sulphate

For melting in a fuel-fired tank furnace it is normal practice to add 3–4 kg of sodium sulphate for a mix designed to give 1000 kg of glass. The purpose is for it to act as fining agent and to assist in dissolving any residual particles of silica which may have floated to the glass surface.

The specification for sodium sulphate is:

Na_2SO_4	95%	
NaCl	3.0	max.
Al_2O_3	0.03	max.
Fe_2O_3	0.16	max.
H_2O	0.4	max.
H_2SO_4	2.0	max.

It is suitable in the form of granular powder of a particle size of about 150 μm.

Sodium sulphate is not used in E glass batches melted in the Pochet furnace or in electrically-boosted unit melters, as sulphates attack the molybdenum electrodes.

4.3.8. Iron oxide (Fe_2O_3)

E glass usually contains about 0.3–0.4% or iron oxide. Because of the infra-red emission and absorption characteristics that iron oxides impart to a glass, its presence assists the fibre forming process. Usually, enough iron oxide is introduced as impurities in the raw materials; should this not provide enough Fe_2O_3 in the glass, extra should be added in the form pulverised iron oxide.

It is important that, once a level of iron oxide has been established which is judged satisfactory, then it should be held constant since changes in iron oxide content will affect the fibre forming process.

4.3.9. The recycling of waste glass fibre

It is common practice throughout the glass industry to return waste clean glass back into the manufacturing process by charging it into the glass melting furnace together with batch. As broken glass it is generally referred to as 'cullet'. With increasing levels of collection of glass containers of all types the proportion of cullet for recycling into the glassmaking process is steadily increasing and has reached levels of over 80% in some cases; the glass quality does not seem to be any the worse for it.

The quantity of waste fibre produced in glass fibre manufacturing operations can vary widely, depending on the products being made and the degree of mechanisation used in the plant; it can be assumed to lie somewhere between 10 and 25% of the glass which was originally melted. This glass, as E glass, contains between 5 and 8% B_2O_3 and is therefore potentially valuable as a raw material. Furthermore, it must be expected, in line with experience in the glass industry in general, that the use of 'E glass cullet' would bring significant economic advantages to the melting of E glass, i.e. more rapid melting, lower melting temperatures, and a saving in energy requirements, quite apart from the saving in raw materials.

In addition, in the case of waste fibre, there would be a considerable saving in the cost of disposing of this very bulky material.

Much work has had to be done to investigate the use of waste glass fibre as a raw material for making E glass. This arises from the fact that waste glass fibre from E glass operations is usually coated with organic material, i.e. the fibre size with possibly, mat binder. Although it is recognised that the organic materials would burn off before any reactions between batch constituents took place, i.e. before the batch reached 650–700°C, they could, in so doing, create local reducing conditions during the glass melting operation. This could, in turn, affect the redox equilibrium of the glass, in particular the equilibrium between Fe_2O_3 and FeO in the glass and, thereby, the infra-red emission of the glass, a factor of considerable importance in fibre forming.

The picture at the moment is not a little confusing, but economic pressure to make use of waste fibre by recycling is such that it must be assumed it is only a question

of time and, perhaps, care in devising technically sound recycling treatments, before the vast bulk of waste glass fibre will be recycled and/or used in some form.

For well over a decade some companies in Japan have simply cut their waste fibre (other than from chopped strand mat) into lengths preferably between 20 and 30 mm, dried it, the fed it separately into the batch charger just upstream from its entry into the furnace. In this way, waste fibre was mixed with batch [13].

In another case, also in Japan, the waste fibre was broken down wet in a grinder, excess water removed in a centrifugal separator until, with a water content of between 2 and 3%, the material was used as a batch raw material [14].

Bearing in mind the extremely high quality standards required of glass for fibre forming, the following approaches seem to take care to clean and purify waste fibre before using it as a glassmaking raw material. In one example, from the United States, the waste fibre is chopped wet, then drained, passed through an oven to burn off all organic matter, ground to give a free-flowing powder, and transferred to a silo in the batch mixing department; from that point onwards, the waste fibre is handled exactly like all other raw materials, i.e. a controlled proportion of waste fibre is included in each batch mix [15]. A similar process seems to have been used in Japan [16].

If batch is pelletised, ground waste fibre can be included in it [17]. An alternative approach proposed (perhaps used) in the United States consists of burning off the organic matter on the fibre, then melting the fibre and passing the molten glass into the glassmaking furnace [18].

It is difficult to obtain a clear picture of the present situation and technology. There are several companies which include recycled waste fibre in the batch up to a maximum of 15%; it is claimed that, above 15%, the glass quality, as determined by fibre forming efficiency, suffers. Sometimes, the quality suffers at levels even below 15% and manufacturers have felt forced to reduce the waste fibre content to lower figures. By preference, waste fibre from the fibre forming department is used as the amount of organic matter deposited on the fibre is low at this stage, and the majority of this is washed off by the various water sprays which cause water to flow through the waste continuously before its removal.

The waste fibre treatment procedure, in general terms, includes the following steps:

- collection of waste fibre from the fibre forming department; this may involve raising the waste fibre out of a cellar;
- crudely cutting the waste into short length of 10–20 mm for easier handling and lower bulk;
- passing the waste fibre through a metal detector and ejector;
- burning off all organic matter at about 650–750°C in a furnace which provides easy access for air; this also changes the characteristics of the fibre in that it becomes very brittle;
- grinding of the clean fibres in a ball mill to give a free-flowing powder passing a 200 mesh; and

- storage or transfer to silos from where the ground waste fibre is used either as a batch constituent or fed at predetermined rates into the batch charger(s) of the melter.

Even with these precautions, some companies, and this includes some large manufacturers, have ceased to recycle waste fibre as they found it lowered the quality of the glass for fibre forming, thus increasing rather than decreasing product costs. The reason for the deterioration of glass quality is believed to be contamination by organic matters rather then material picked up during the grinding process. One must conclude that waste fibre recycling will become established, even if some technical problems remain unresolved at this date.

It could well be that, for critical products, such as fibre for fine yarns having filament diameters of 7 μm or less, glass made only from batch should be used; however, for less critical products such as are made into direct chopped fibres (17–24 μm) or rovings for weaving or winding (14–17 μm), or even chopped strand mat and continuous strand mats (11–13 μm), recycling of waste fibre could well become standard practice.

4.4. Handling, weighing, and mixing of raw materials into batch

Batch is the mixture of weighed raw materials carefully blended to give homogeneous glass of the intended composition.

For obvious reasons batch preparation is a critical operation in glassmaking and the following conditions must be met:

(1) The raw materials (and this includes recycled waste fibre, if used) must be received, stored and handled in such a way that their compositions are known when they are used, and that segregation according to particle size is avoided. In cases where the composition can vary from one delivery to the next, arrangements must be made for each delivery to be stored separately. In any case, each delivery must be analysed or, better, the supplier should be under an obligation to provide a certified chemical and particle size analysis with each shipment.

(2) The weighing of each material must be carried out to a degree of accuracy which ensures that the properties of the glass, and that means its composition remains within specified limits.

(3) The handling of raw materials must not release dust into the atmosphere. This is an objective which can only be met in a fully automated batch plant in which all materials are handled in totally enclosed systems. Depending on the location of the plant this is not always possible; at least some of the materials will be received in bags which have to handled, even if by fork lift truck. However, all batch plants should be designed with the objective to be dust-free, and constant vigilance must be applied to ensure cleanliness and good housekeeping; if not, conditions will soon arise which will undermine control over the glassmaking

4.5. Production of E glass

This section will deal with that part of the process in which batch is fed into the melting section of a glassmaking furnace (i.e. the melter) and is converted into homogeneous molten glass ready to be used for the manufacture either of marbles for subsequent remelting and manufacture into fibre, or directly into glass fibre.

4.5.1. The characteristics of E glass from the point of view of glass melting

The quality requirements of glasses suitable for attenuation into continuous glass fibres are very high. E glass is not an 'easy' glass to make to the high standards required, for the following reasons:

(1) The fusion of the raw materials needs a comparatively high furnace temperature in view of the absence of alkali metal oxides as fluxes.
(2) At the high founding temperatures employed, E glass is very corrosive on most refractories: technical progress in glass fibre manufacture has largely been linked to advances in refractory technology, leading to a choice of materials giving reasonable life and good quality of glass throughout the campaign of a furnace.
(3) E glass contains two volatile constituents, B_2O_3 and F_2. For a given furnace the amounts lost depend on furnace temperature, rate of melting (i.e. output of glass in tons/day) and water content of batch. The losses should obviously be minimised and kept constant in order to obtain glass of constant quality and properties. This means that the furnace should be operated in such a way that the melting history of any unit of glass leaving the furnace is the same. Hence the objectives become:

   (a) Constant batch quality, i.e. constant composition, varying only to the extent that small modifications are necessary due to changes in composition of a raw material.
   (b) Constant pull on furnace, i.e. tonnes of glass per day. Its importance lies in the fact that losses of B_2O_3 and F_2 by evaporation are also a function of time.
   (c) Constant furnace conditions, i.e. temperature, pressure, flue gas composition, etc.

   (b) and (c) are interrelated. A change in pull will alter the fuel requirements of the melter, the flow of glass in the melter, losses of volatile components, etc. A change in pull can result from changes of the downstream operation, e.g. a change in type of fibre required, or a bushing being out of commission. In short, many good reasons will be advanced why some changes in pull cannot be avoided. The aim must always be to minimise the rate of change, allowing only small changes to take place at any one time, and to correct the operating conditions in small steps frequently rather than in large steps infrequently.

4.5.2. Production of E glass in a Unit Melter

The most common furnace employed for making E glass is of a type known as a Unit Melter. This is a small tank furnace developed in the 1940's by the container glass industry for glasses which were not required in very large quantities. The design is characterised by having a high length-to-width ratio, usually not less than 3 : 1, and by being fired by opposing gas or oil flames across the width of the furnace. For economic reasons, the bulk of the combustion air is now preheated in a metal recuperator or in a regenerator. A schematic drawing of a unit melter is given in fig. 4.2.

Batch with or without waste fibre, is fed in at one end of the furnace either through one or both of the side walls, or through the end wall; the properly melted glass is withdrawn at the opposite end under a skimmer block (S) located in a narrow channel (C) (see fig. 4.3).

The description that follows must be taken in general terms. There are many points of detail where designs and procedures differ between companies. In view of the highly competitive nature of the business and the consequent secrecy surrounding the technology, time is always needed before relevant technological experience comes to light (for a specific example, see Day [19]).

For details of furnace construction and principles of operation the reader is referred to the work by W. Trier on glass furnaces [20].

4.5.3. Design parameters of unit melters for E glass

(1) Melting area.
For established plants where the production plan is pretty firmly established, and without supplementary electric heating (called electric boosting), a design figure of 1.2 m^2 per ton per day is now normal. For new plants, where experience is lacking and has first to be acquired, it is better to be conservative and design the furnace on the basis of 1.5 m^2 per ton per day, thereby allowing production to be increased as experience is gained and as the market is developed. Knowing the initial daily tonnage required, and having decided on the length-to-width ratio of the melter (somewhere between 3 : 1 and 4 : 1), the dimensions of the melting area can be established.

(2) Depth of glass in the melter.
Compared to other glass furnaces, furnaces for making E glass are shallow, more in line with furnaces for making coloured glasses. This is due to the presence of iron oxides in the glass which significantly reduces the heat transmission from the surface of the molten glass to the floor. Thus the floor tends to be colder and, in order to avoid devitrification which, in the case of E glass, occurs at temperatures below 1130–1140°C, the depth has to be kept small.
The depth of glass varies between 500 and 1200 mm, depending partly on plant experience, on furnace size, types of refractories chosen for the floor (including any insulation applied) and, in more recent times of increasing importance, on

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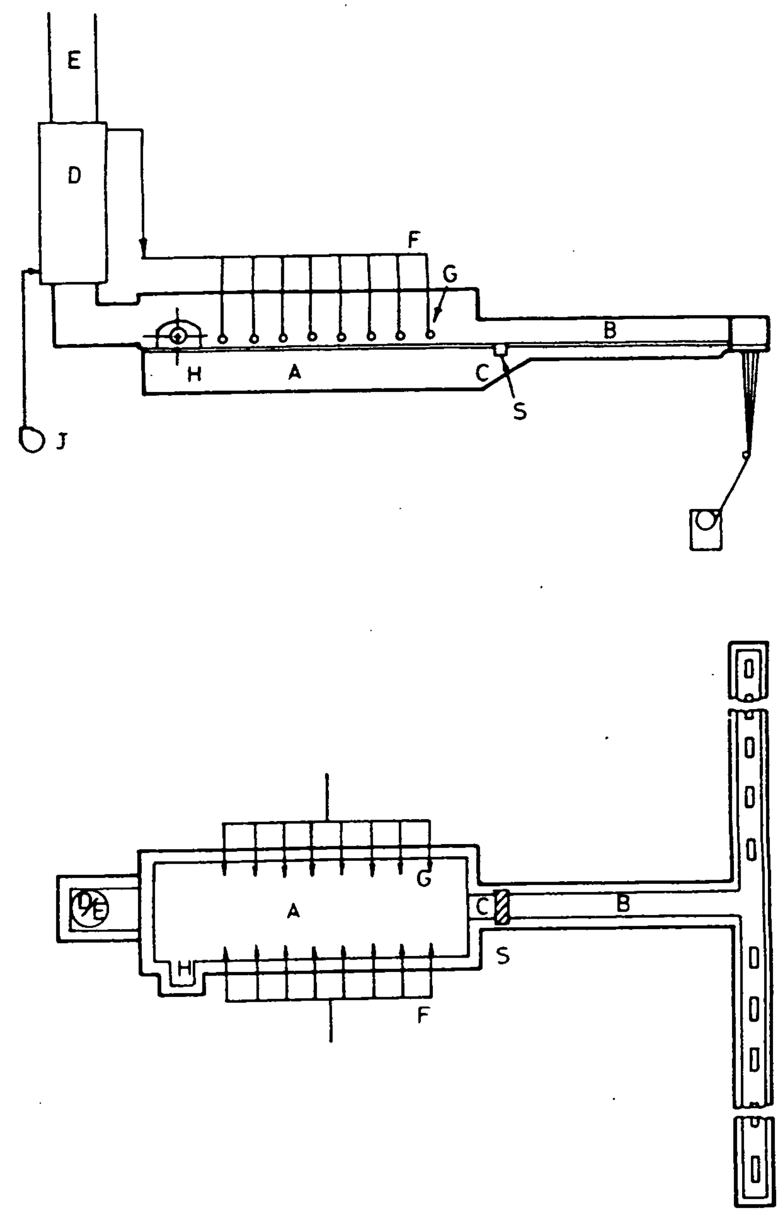
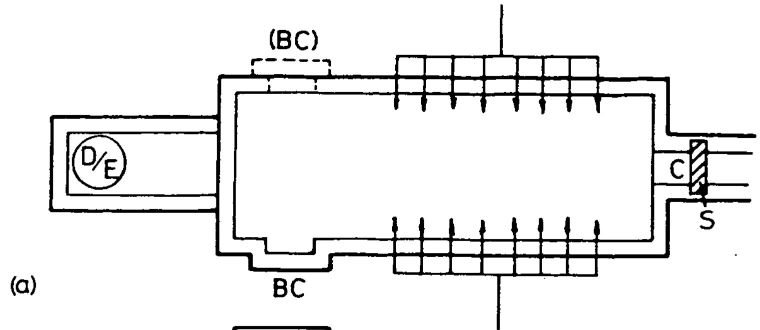
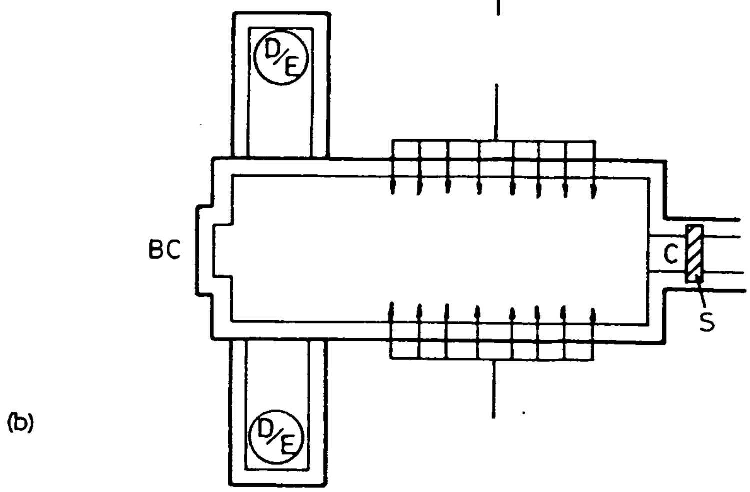


Fig. 4.2. Diagramatic sketch of a unit melter for the manufacture of E glass fibre. Mixed raw materials (batch) are charged through the doghouse H into the melting chamber A where they are heated and fused by flames through burners G supplied with fuel (gas or oil) and preheated combustion air F supplied from a fan J. Waste gases leave the melter through a recuperator D and a flue E. The molten glass leaves the melter via channel C, passes under a skimmer block S into the conditioning section of the forehearth B, and then into the bushing forehearth where glass is withdrawn through fibre forming furnaces (bushings).





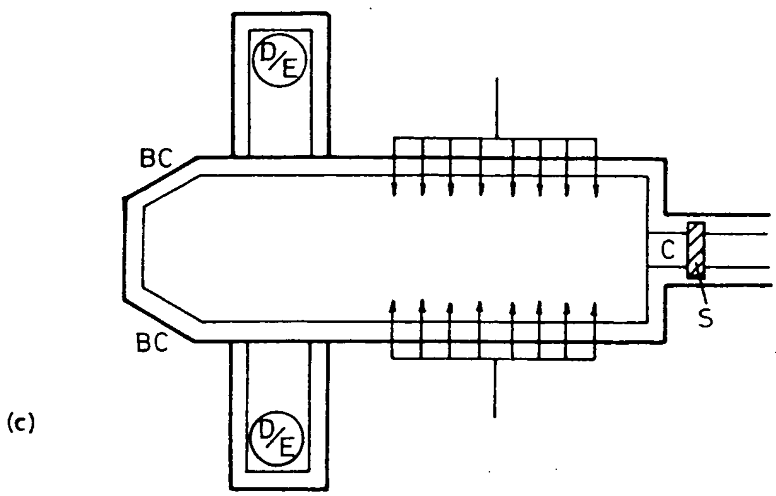


Fig. 4.3. Unit melter showing alternative arrangements for batch charger(s), recuperator(s) and flue(s) which vary with the size of melter. (BC = batch charger. D/E = recuperator and flue.)

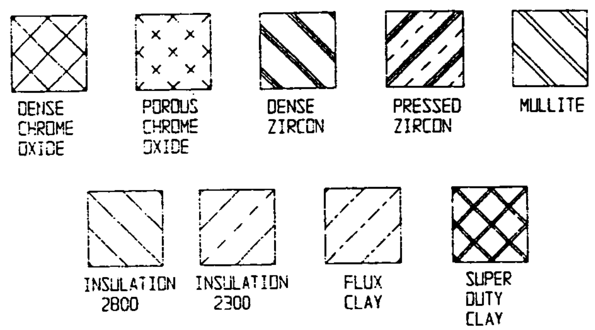


Fig. 4.4. Legend identifying specific refractories referred to in Chapter 4.

whether the melter has electric boosting. The danger of devitrification on the floor is greatest for small furnaces without electric boosting. For such furnaces a depth of 610–630 mm is satisfactory for one rated at 10–15 tons/day; this can rise to 1000 mm for one of 40 tons/day, and to 1200 mm for one rated at 75 tons/day. The depth has to be decided with care, as the floor in a melter that is too shallow will overheat and cause premature furnace failure.

(3) Choice of refractories.

(a) *Side walls.* Under normal operations the most severe corrosion takes place along the contact line between molten glass, refractory, and furnace atmosphere, called the flux line. The only suitable glass contact refractory for E glass and in the side walls is dense chrome oxide, now generally available in a high-quality isostatically pressed form. The layer of chrome in the side walls can be 150 mm thick and is often installed even thicker in the downstream half of melters where the batch has melted and where the glass reaches the highest surface temperatures. The chrome is usually backed with dense zircon or, more recently, with porous chrome, which, as the name implies, is a less dense, more porous form of chrome refractory and therefore has greater thermal shock resistance.

In smaller furnaces, say, of up to 25–30 tons/day melting rate, the dense chrome and its backing constitutes all the refractory for the top 100–120 mm (fig. 4.5). In the lower section, where the temperature of the glass in contact with the sidewall is less, the chrome blocks and their backing are further backed up with good quality clay blocks and insulation. The resultant gap at flux line level is used to provide air cooling from fans to reduce the rate of flux line corrosion.

For large furnaces, the side walls are more substantial and can consist of chrome blocks 150 mm thick backed by dense zircon blocks of the same thickness with further backing of clay blocks (fig. 4.6). Alternatively, the

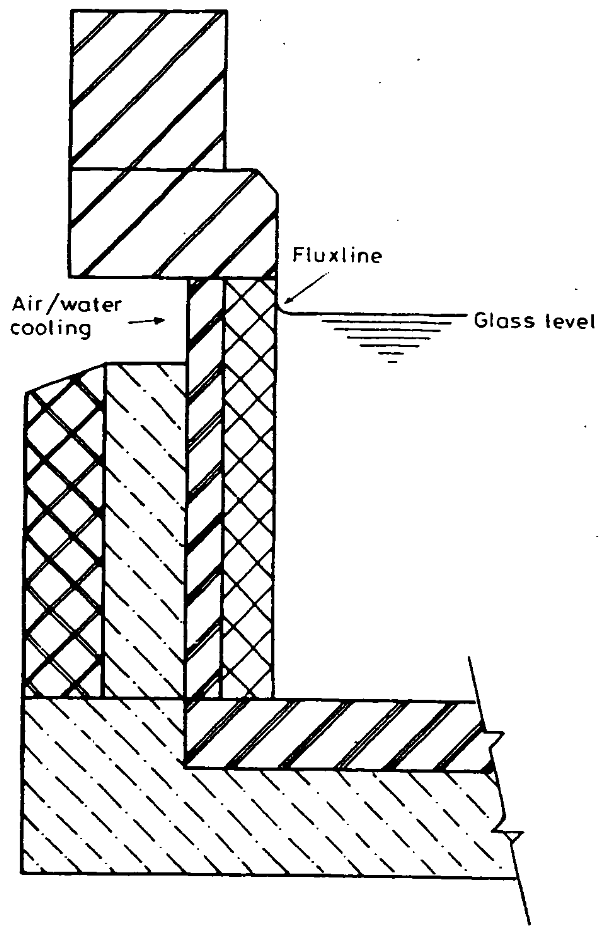


Fig. 4.5. Arrangement of side walls for small to medium-sized melters (max., say, 30 tons/day output). Initially air cooling, then later, cooling by water boxes or pipes, is applied to the blocks at the flux line. (For key to refractories, see fig. 4.4.)

chrome can be 300 mm thick when the zircon is omitted. Despite the fact that air or water cooling cannot easily be applied at the flux line (see Section 4.7.2.1 (5)) campaigns in excess of six years are being achieved.

(b) *Bottom*. Over most of the floor area the glass contact refractory is dense zircon (100-150 mm thick) backed by clay blocks and insulation (not shown). For about 1 m each sides of any rows of bubblers, however (see Section 4.5.4.5 below), the glass contact refractory should be dense chrome to a depth of 100–150 mm. This is to take care of the higher corrosion rate in-

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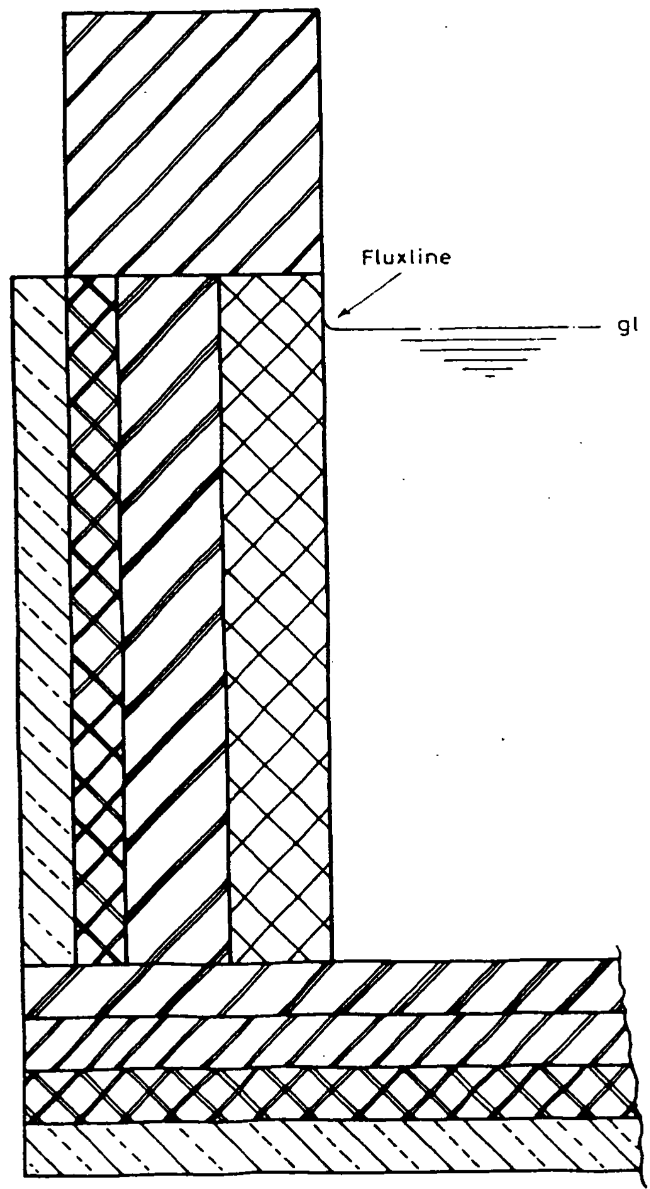

Fig. 4.6. Arrangement of side wall refractories for large unit melters (30 tons/day and above). Sometimes the thickness of chrome comprises the chrome as shown plus the zircon backing it. (For key to refractories, see fig. 4.4.)

duced by the more rapid flow of glass caused by the upward movement of air from the bubblers.

(c) *Melter superstructure.* The melter above the tank blocks can be constructed of either mullite or silica; in view of the high operating temperatures used (1580°C), high-alumina mullite is usually preferred, but is more expensive. The side walls are 220–300 mm thick and are normally set back from the inside edge of the glass contact refractories by about 150 mm; they are carried on their own steelwork attached to the furnace stanchions. The height between tank blocks and side walls below the crown varies with the width of the furnace; for a melter about 3000 mm wide inside the glass contact refractories, the height of the side walls would be about 450–500 mm.

The crown is self-supported on angle irons attached to the furnace stanchions. It is usually constructed of mullite 220–300 mm thick, is then covered with 75–150 mm of insulation, followed by a blacket of fibrous kaolin with an outer surface of aluminium foil. This prevents batch dust in the atmosphere reaching and then corroding the refractories. The rise of a crown for a furnace of 3 m width inside is about 350 mm. Although mullite is the preferred material, crowns made of silica can also be used under carefully controlled conditions; they are much cheaper.

The burners are inserted through special burner blocks inserted in the side walls opposite one another. They are usually made of medium-dense zircon and are placed with their centres about 270 mm above the glass contact refractories and 600 mm apart. Similarly the bricks holding the exit tubes from the batch feeders are also of medium-grade zircon with their centres 200 mm above normal glass level. The reason for not using the dense zircon in these locations is that more porous grades possess a higher thermal shock resistance and therefore less likely to spall.

4.5.4. Special features

(1) The doghouse.

The part of a tank furnace into which the batch is charged from the batch charger is known as the doghouse. This is an area where corrosion of refractories is heavy, at least in part due to thermal shock resulting from cold materials coming into contact with hot refractories. The refractories used in this part an E glass furnace are either dense chrome backed by dense zircon and fire clay or blocks of dense zircon itself (fig. 4.7). Zircon without chrome facing is believed to be adequate since the cold batch keeps the sidewall temperatures somewhat lower than is the case further down the melter. Batch is usually fed by a single or twin screw feeders pushing batch in through the wall of the furnace about 150–200 mm above the normal glass level.

(2) The channel.

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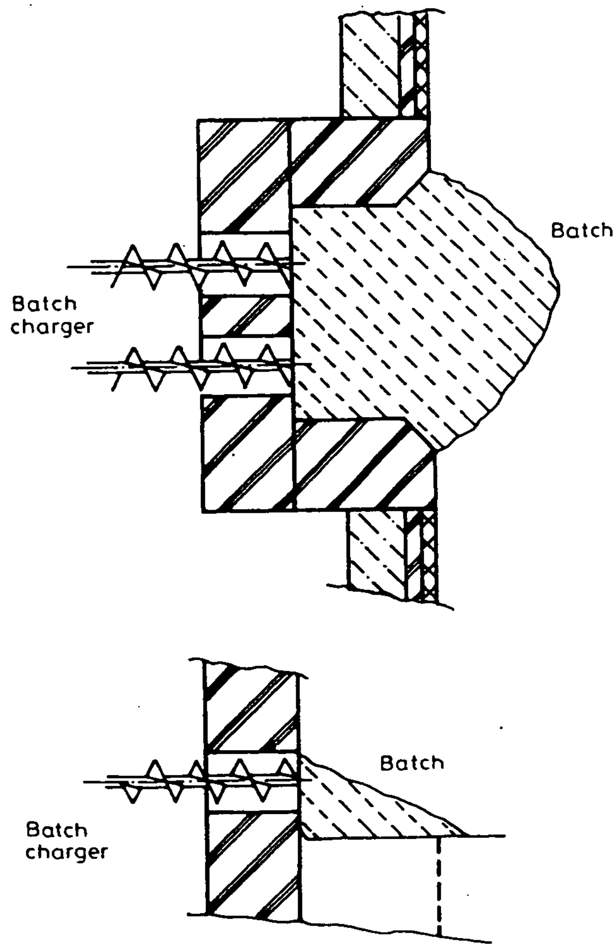

Fig. 4.7. Typical arrangement for the doghouse. Chargers with single or double screws can be used.

narrow channel (fig. 4.8) and passes from there through as conditioning section to the forehearth. For a 15 tons/day furnace this block typically measures about $1000 \times 200 \times 150$ mm, where the 200 mm dimension governs the depth of immersion. It is made of pressed zircon or mullite and is covered with platinum-rhodium alloy, usually 1 mm thick where immersed in the glass and 0.5 mm on the top; the alloy covering should extend some distance, say 150 mm, into the channel side walls, so that, as the side walls corrode away, the skimmer block and its protective covering remain intact. The refractory of the skimmer block

should have a low iron content in order to avoid contaminating the platinum alloy cover and, possible, its early disintegration. It is worth noting that, for reasons of security, the construction of a furnace should be carried out in such a way that the metal-covered skimmer block can be inserted during the final stage of furnace construction.

This channel–skimmer arrangement is unusual in the glass industry. In most tank furnaces the glass is withdrawn from the melter through a channel located on the floor, sometimes even below the floor, of the melter and leads to the 'working end' which is a totally separate structure. The second unusual feature is that the depth of immersion of the skimmer is rather low. An effective glass depth in the melter is at least 610 mm. If the floor of the channel is 150 mm above this, then the depth of glass as it enters the channel is 460 mm. Since the top edge of the skimmer is about 50 mm above glass level, and if the skimmer block is 200 mm in height, this leaves an opening of 310 mm in depth under the skimmer. This is large bearing in mind the flow rate of the glass. More recently, skimmer blocks giving depths of immersion in excess of 300 mm have been installed. Any lowering of the passage of glass out of the melter holds back the hotter glass originating from nearer the surface of the melter, thus reducing the temperature of the glass flowing into the forehearth; this makes it easier to condition the glass to the temperature suitable for fibre forming (see also beginning of Section 4.6.)

An alternative method is to construct the end wall in full and allow the glass to pass out of the melter through a platinum-lined hole constructed through the end wall blocks at a desired height.

(3) The exit port.

The exit passage for the flue gases passing from the melter to the recuperator should be constructed of mullite, or preferably of pressed zircon. Corrosion is usually heavy, not only due to the velocity of the gases, but also due to batch dust carried in the flue gases. The walls below the recuperator will also be subjected to corrosion by condensed boric oxide and other glass constituents flowing down from the recuperator. These materials are now allowed to flow back into the melter, thus eliminating the problem of collecting and removing them. However, since corrosion can be heavy the floor should slope slightly downwards towards the glass surface in the melter and should be lined with dense chrome tiles.

(4) The bubblers.

In every tank furnace there is some position downstream towards the channel where the surface temperature of the molten glass is highest. At this 'hot spot' there is a natural upward current of glass which is, of course, balanced by downward currents elsewhere in the furnace (fig. 4.9).

In addition to these major currents there are minor ones, of which the surface current is technologically important because this current can carry incompletely fused raw materials towards the channel. For this reason one or more rows of

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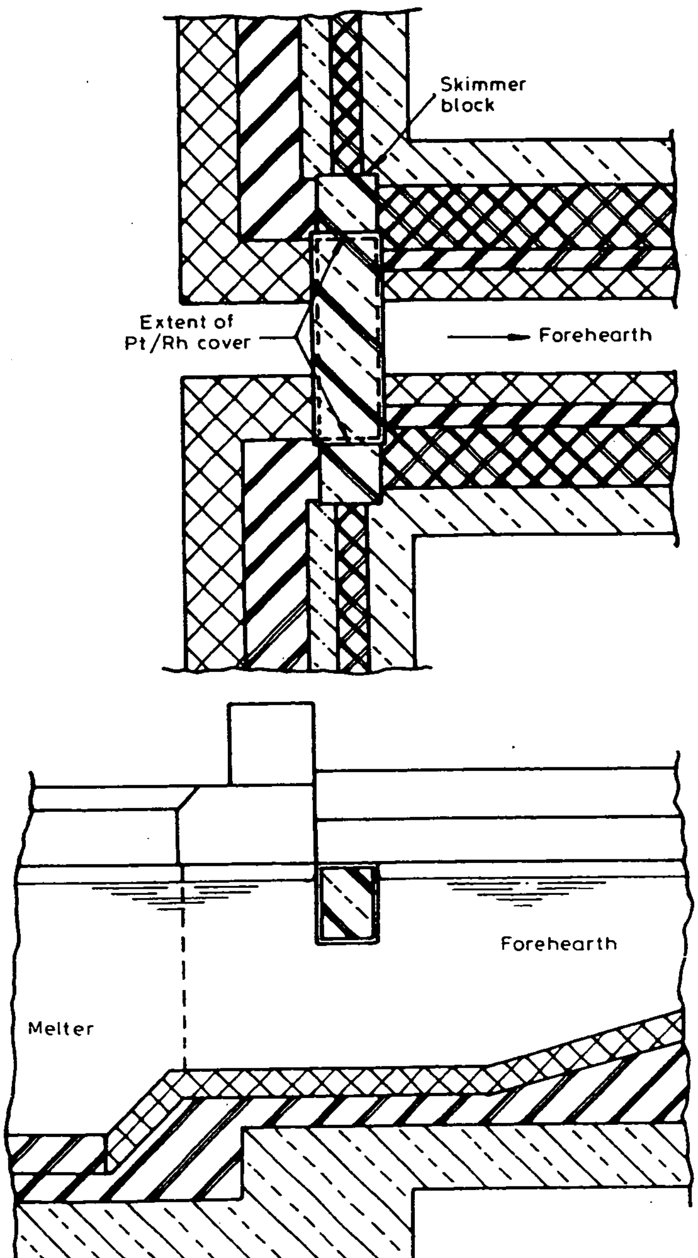

Fig. 4.8. Normal channel and skimmer arrangement in unit melters for E glass manufacture.

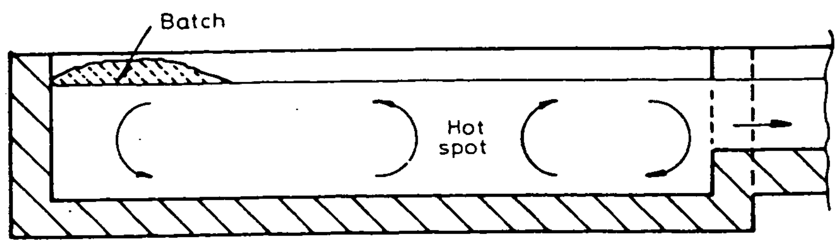

Fig. 4.9. Diagrammatic representation of the zone of high temperature in a glass tank furnace (superstructure not shown). This zone gives rise to the major convection currents. In E glass unit melters, one or more rows of bubblers are usually located in the floor below the 'hot spot', thus encouraging the normal convection currents.

bubblers are placed across the width of the furnace in the area of the hot spot to achieve the following:

(a) to increase the velocity of the currents and thereby aid in homogenising the glass, and
(b) to act as a barrier across the width of the furnace, thus preventing incompletely fused raw materials from flowing towards the channel and the forehearth.

Typical bubbler tubes consist of 80Pt-20Rh or grain-stabilised 90Pt-10Rh tubing, of 10 mm external diameter and 0.75 mm wall thickness. The tubes protrude through the bottom blocks of the furnace by 150 mm and are made sufficiently long so that they can be soldered into copper pipes of 20 mm internal diameter which are supported in position from below the furnace (fig. 4.10).
The holes through the floor blocks can be 40 mm in diameter in the lower layer of blocks (clay) and 30 mm in the upper layers of blocks (dense chrome). Typically, the distance between adjacent bubblers is 340 mm with the distance between a bubbler and the furnace sidewall increased to 450 mm to avoid causing accelerated rapid refractory corrosion in this area.
The flow rate of clean dry air through each bubbler is about 0.25 m^3 per hour. The flow of air is controlled manually and separately to each bubbler.
A single line of bubblers is the simplest arrangement. Some manufacturers favour a double staggered row as a safeguard should a bubbler fail. It is, however, possible to replace a non-functioning bubbler while the furnace continues in operation by drilling a hole from below and inserting a new bubbler near the position of the one that has failed: this drilling and manipulation requires special equipment and is usually carried out by companies specialising in this kind of work.
Some manufacturers install not only one or two rows of bubblers at the 'hot spot', but also a parallel one under the batch blanket, i.e. where the fusion of

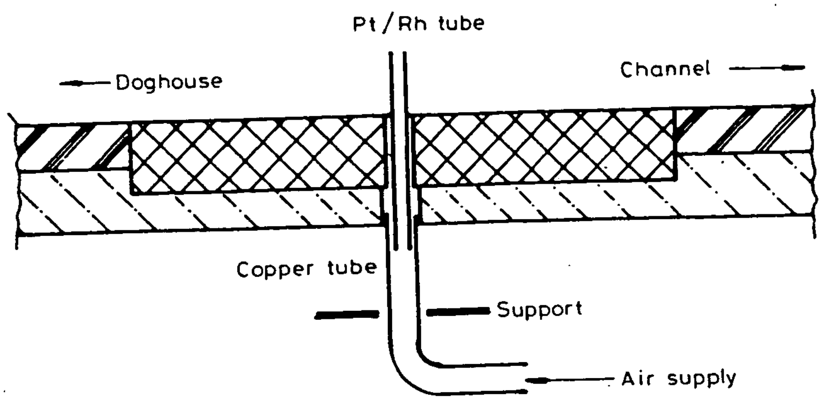

Fig. 4.10. Cross-section of melter floor through a bubbler position. Because of the increased rate of wear of floor refractories in the region where the bubblers create additional upward glass currents. the normal dense zircon floor tiling has been replaced by dense chrome for about 1 m upstream and downstream of the bubblers.

raw materials takes place. This is believed to create a more rapid surface current towards the centre of the melter and the other row of bubblers, thus spreading the floating batch over a larger area and accelerating its fusion. However, this arrangement also carries with it the risk of entraining batch in downward currents with the result that unmelted particles could eventually pass under the skimmer into the glass for working and cause problems in fibre forming.

4.5.5. *Design factors governing the campaign length of a unit melter for E glass*

All glass furnaces have a limited life governed by the rate of corrosion of refractories and the consequent failure of the furnace as a structure. The first direct-melt furnaces making E glass had a campaign life of 9 months by which time a large proportion of the best then available refractories (zircon) had dissolved in the glass (with serious adverse effects on glass quality) and to an extent that the structure became unsafe or even failed catastrophically. With the development of chrome refractories, improvements in their quality and the ability to form larger blocks, improvements in automatic control of furnace operation and detailed study of reasons for failure and improvements in the finer points of design, the campaign life of E glass unit melters can now reach 6–7 years.

The campaign life of furnaces has been increased by a number of factors:

(1) The availability of dense chrome blocks of over 200 mm (8″) thickness. These would obviously last longer and can be placed in the more critical areas, i.e. where the rate of corrosion is more severe, like the downstream section of the melter between bubblers and exit. The side walls can be made of tiles standing

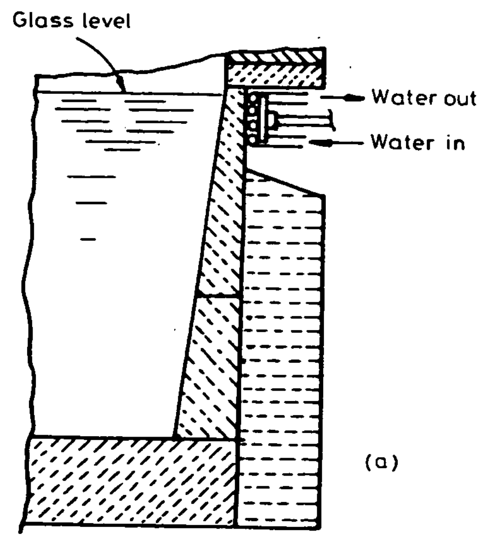

Fig. 4.11. Alternative arrangements for preventing side wall blocks falling into the melter. A[n] example of flux line cooling by means of water pipes is also shown.

on edge, the chrome tile backed by dense zircon. then by clay blocks (see fig 4.5) or the chrome blocks can be laid on their side and laid one on top of th[e] other. backed by dense zircon, or porous chrome, or directly by clay blocks (se[e] fig. 4.6). It is all a question of assessing the strength and weaknesses and cos[t] of each arrangement related to the longer term manufacturing programme.

(2) A critical area of every glass tank furnace is the flux-line since corrosion i[s] most severe at the contact line between molten glass. refractory and furnac[e] atmosphere. For this reason the design shown in fig. 4.5 is usually provide[d] with artificial cooling, initially by fan air, followed later by water-cooled pipe[s] or boxes or. in extreme cases, by water sprays. (See fig. 4.11.) The arrangemen[t] shown in fig. 4.5 runs the risk that. as corrosion proceeds, one or more o[f] the tiles become unstable and fall inwards into the glass. Many reasons ca[n] contribute towards this situation. like buckling during heat-up. if the expansio[n] joints were not large enough. accidental fracture of a block, etc. By installin[g] the side walls at an angle (fig. 4.11), this risk is reduced significantly; obviousl[y] the arrangement of fig. 4.12 is designed to provide a longer furnace campaig[n] [21].

(3) Overall. the design of any glass furnace develops with experience of the use[r] and aims to achieve a balance in which the rate of wear of the most critica[l] parts is balanced by that of the less critical parts. And this includes some o[f] the auxiliary equipment like the hot section of the recuperator (see below).

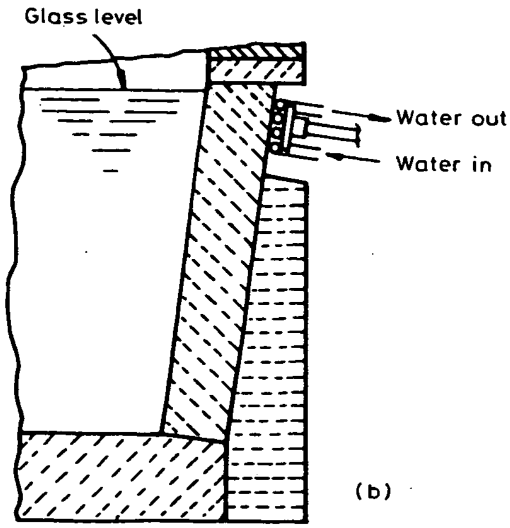

Fig. 4.12. Alternative arrangements for preventing side wall blocks falling into the melter. An example of flux line cooling by means of water pipes is also shown.

4.5.6. Services and safety

This section covers the melter only; for the installation of a whole plant the services should all be combined.

(1) Electricity.
There should be separate circuits for:

(a) Combustion air fans.
(b) Gas compressor premixer, or oil tank heating, line heaters and pumps.
(c) Water pumps and cooling radiators.
(d) Instrumentation and all controls.
(e) Lighting and other miscellaneous loads.

In all cases a standby generator is required to safeguard the furnace and other critical equipment in the event of a power failure. For the furnace, at least the following services should be connected to the standby generator:

(a) Combustion air fans and air compressor for atomisation of oil, if oil firing is used.
(b) Gas compressor or premixer, or pumps and heaters of an oil firing system.
(c) Furnace cooling water pumps and all electrical motors associated with water cooling.

(d) Instrumentation and all electrics associated with control of the furnace operation.
(e) Batch charger(s).
(f) Emergency lighting.
(g) Forehearth gas/air compressors (see Section 4.6.2.4.).

All key services, such as combustion air fans, gas compressors, oil pumps, water pumps, cooling radiators, etc. should be installed in duplicate with automatic change-over in case of failure of one of them. All such equipment will have an operating indicating light in the furnace instrument panel so that, in the case of an automatic change-over occurring, this fact will be evident and will cause the reason for the failure to be immediately investigated and remedied.
All motor starters must comply with the regulations of the power supply authority or company. Most starters are fitted with breakers or trip-out devices which cut power to the motor if there is an overload, or if there is a sudden reduction in power. In some areas short-term power reductions lasting no more than 1–2 s can occur when changes are made by the supply company. These can cause havoc in a plant if fans, pumps and compressors suddenly trip out, and can even start the emergency power supply. This can be avoided if:

(a) all switches which require resetting after tripping out only actually trip out after a power supply interruption of not less than 5 s; and
(b) the stand-by diesel generator comes into operation only after 10 s of a power failure.

(2) Fuel for combustion.
Natural gas or LPG or oil can be used. Of these LPG is so expensive by comparison with the alternatives, that it need not be considered here. The manufacturers of metal recuperators (see below) used to issue rather stringent specifications for certain minor components of the fuel, such as:

– maximum sulphur 1%
– maximum vanadium pentoxide 10 p.p.m.

Such a tight specification is no longer needed since the hot areas of the recuperator are self-protected by a condensate of B_2O_3 which shields it from attack. The sulphur content of fuels is currently more important in connection with atmospheric pollution: a high sulphur content will call for a greater investment in pollution control equipment.
The fuel consumption of all furnaces is a critically important factor for the economics of a plant. Since the products are ultimately sold in terms of weight, the factor to control at the glassmaking stage is the cost of fuel per unit weight of glass melted, i.e. cost/kg. For E glass, this is higher than for most commercial glasses in view of the higher melting temperatures employed and the lower specific melting rate. It is also a function of

(a) the size of the furnace, since the specific heat losses will decrease with size of furnace;
(b) the design of the furnace, in particular the thickness of refractories and, of this, the amount of insulation installed;
(c) the age of the furnace; fuel consumption will increase with age as refractories wear and heat losses increase;
(d) the pull on the furnace, i.e. tonnage of glass produced per unit time. The furnace is thermally most efficient at its maximum pull. Any reduction in pull, occasioned perhaps by market conditions, will permit a reduction in operating temperature and therefore, of fuel consumption, but this will not be large enough to compensate for the heat losses which stay, for all intents and purposes, constant and independent of the amount of glass melted; and
(e) whether oxygen is used instead of air in whole or in part for the combustion process as this will alter numerous parameters of the furnace arising from the fact that there is less or no nitrogen to be uselessly heated up , e.g. size of combustion chamber and waste gas ducts.

The specific fuel consumption of E glass unit melters related to size and its effect on age of furnace is shown diagrammatically in fig. 4.13. This figure includes a line for electricity consumption, a cost which, in connection with furnace operations, is sometimes overlooked. The specific fuel consumption of a new melter will start on the lower line and will, with time, rise to reach the top line or more, depending on the point at which it is decided that, all factors considered, the melter should be shut down for a rebuild.

In many parts of the world, the supply of fuel is a matter which requires special arrangements and is therefore likely to be subject to failure on occasions. Apart from the need to install generous storage facilities, there is also the need for an alternative supply in case of need. Thus diesel oil, natural gas or LPG can all act as standby for heavy fuel oils. For most alternatives, burners are now available which can handle not only oils but also gases, thus permitting change-overs without any adjustments to burners or interruption of the operation.

Heavy oils must be heated in their storage tanks, in the supply pipes to the pumps and, beyond the pumps in all the supply lines to the burners, since these can only function correctly if the oil is supplied at the correct viscosity, i.e. for a given oil, at the correct temperature. This requires the following:

(a) A well-insulated ring main around the furnace in which oil circulates rapidly through one or more thermostatically-controlled line-heaters which keeps the oil at that temperature at which the its viscosity leads to good atomisation for combustion;
(b) Thermally insulated and, if necessary, heated offtake pipes from the ring main to individual burners which should be of small bore and minimum length, the length being the same for all burners; and
(c) In locations where the supply of heavy oil may be of varied origin different temperatures will be required to provide oil at the correct viscosity. Since

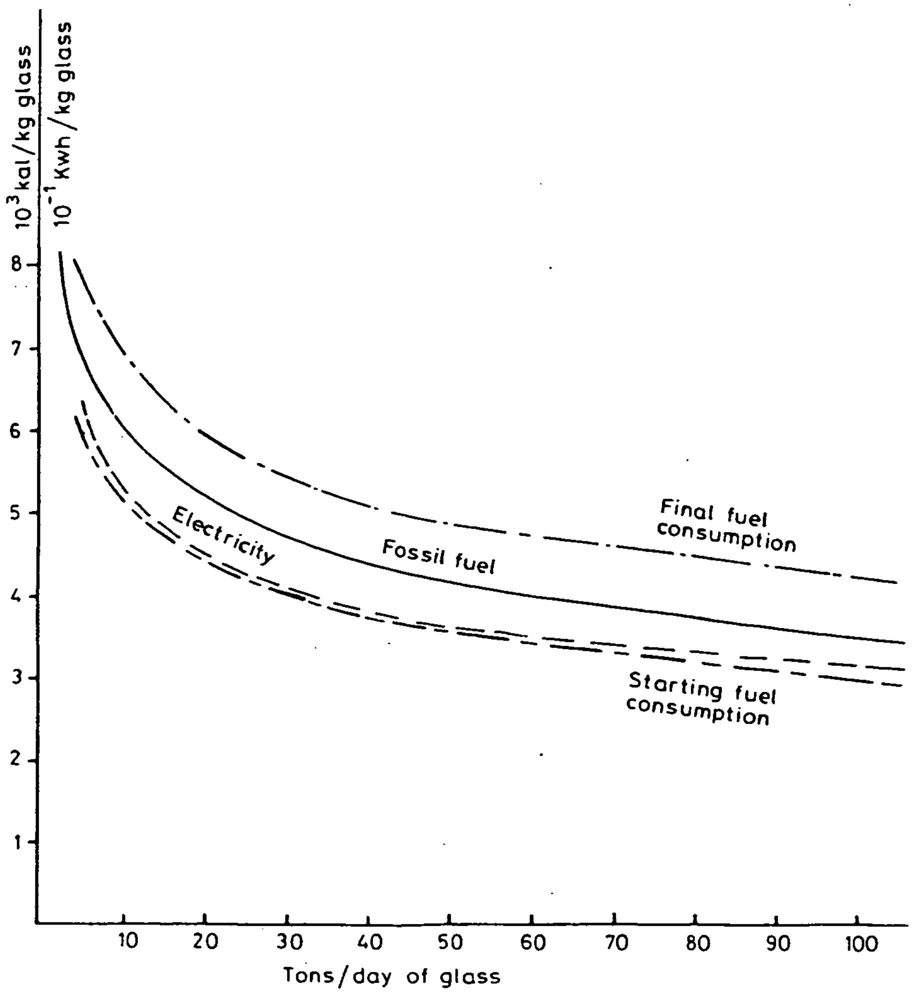

Fig. 4.13. Fossil fuel and electricity consumption per kg of E glass from unit melters of varying design rates of daily production.

such changes in oil supply also imply transitional mixtures from various sources, the only effective method of controlling the viscosity is to install automatic controls by which changes in viscosity are compensated for by changes in the temperature to which the oil is heated. This adjusts to the temperature at which the oil is circulated so that the viscosity of the oil reaching the burners remains unaffected by changes in oil supply.

(3) Combustion air.

Combustion air is needed to provide the quantity of air for the fuel to burn. In the case of oil-firing a small part has to be used as compressed air to atomise the oil on its exit from the burner. In either case the main part of the air (known as 'secondary air') is provided by a combustion air fan of a size sufficient to supply 15 m^3 or air at NTP per litre of oil used. The fan must be large enough to provide enough air under maximum demand conditions which are likely to arise towards the end of a furnace campaign. This air is passed through a recuperator or regenerator for preheating to a temperature of about 700°C. There is therefore

(a) a primary air supply in the case of oil-firing for atomisation; the quantity of air required for bunker oil is about 2.5 m^3 per litre of oil at 1.5–2.0 kg/cm^2; this is not preheated. It can come from a separate compressor, or in the case of low pressure atomising air can be part of the cold air supplied by the main combustion air fans.

(b) secondary air fans of sufficient size. These are likely to be large (i.e. over 100 h.p. for a 15 ton/day furnace) and must therefore be mounted on vibration-absorbing concrete pads. The air leaving a fan of this type is at about 1500 mm w.g.

(c) air to operate the air damper, if used, and to cool the seal ring between recuperator and exit flue from the melter. Any air required for firing the forehearth (see below) is best treated separately.

(4) Recuperators and regenerators.

Recuperators or regenerators are used for preheating air used for combustion. If oxygen is used instead of air these may not be necessary. Recuperators are heat exchangers in which the outgoing hot waste gases transfer some of their energy to cold air needed for combustion by transfer through pipes of metal or ceramic. In the manufacture of E glass, the heat exchanger is usually a metal recuperator of which there are basically two types.

The Escher recuperator (fig. 4.14) consists of joined sections of two concentric tubes constructed of special stainless steels in which the innermost tubes carries the flue gases and the secondary air is preheated by passing through the annulus between outer and inner tubes, sometimes in counter flow. The whole recuperator usually consists of two or more sections with a typical airflow arrangement as shown in fig. 4.14. Special suspension and expansion arrangements have to be provided. At the end of a campaign, when the furnace is shut down for rebuilding, usually only the bottom hot end section of the recuperator needs repair or, at worst, replacement.

The cage-type of recuperator (fig. 4.15) is one in which the air to be preheated is passed through high-temperature stainless steel pipes located inside the flue through which the hot gases pass. It is also used widely in association with E glass melters.

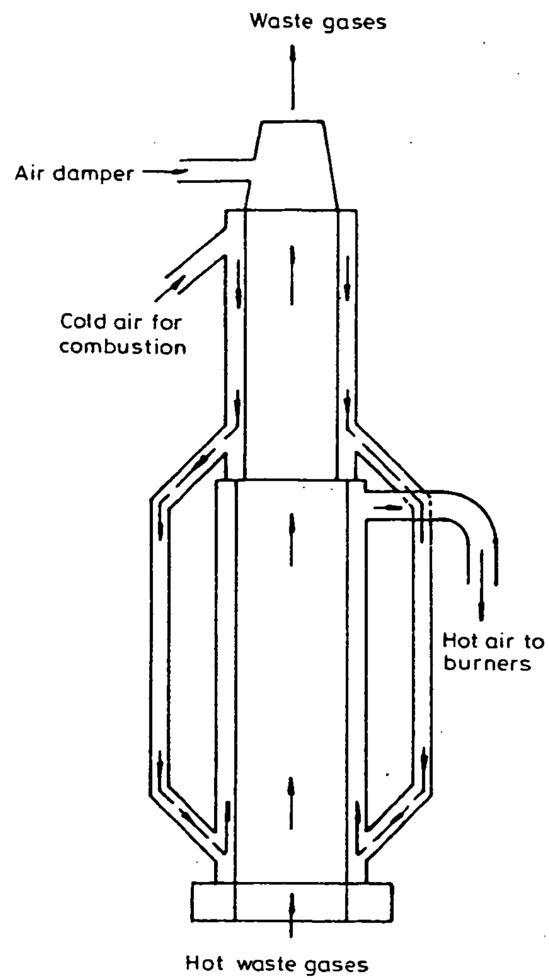

Fig. 4.14. Escher type of metal recuperator. Cold air required for combustion is preheated by passing it through the annulus formed by two concentric tubes.

In a regenerator, the waste gases pass alternatively through one of two chambers in which suitable refractories are stacked in such a way that the hot flue gases pass between them and thereby transfer some of the thermal energy to the refractories. After about 20 min the flue gases are diverted to pass through the alternative chamber, while cold secondary air is passed through the first chamber in the reverse direction, thus absorbing thermal energy. The air then passes as preheated combustion air to the burners. For cross-fired furnaces, as is the case for E glass unit melters, this method of preheating the secondary air means

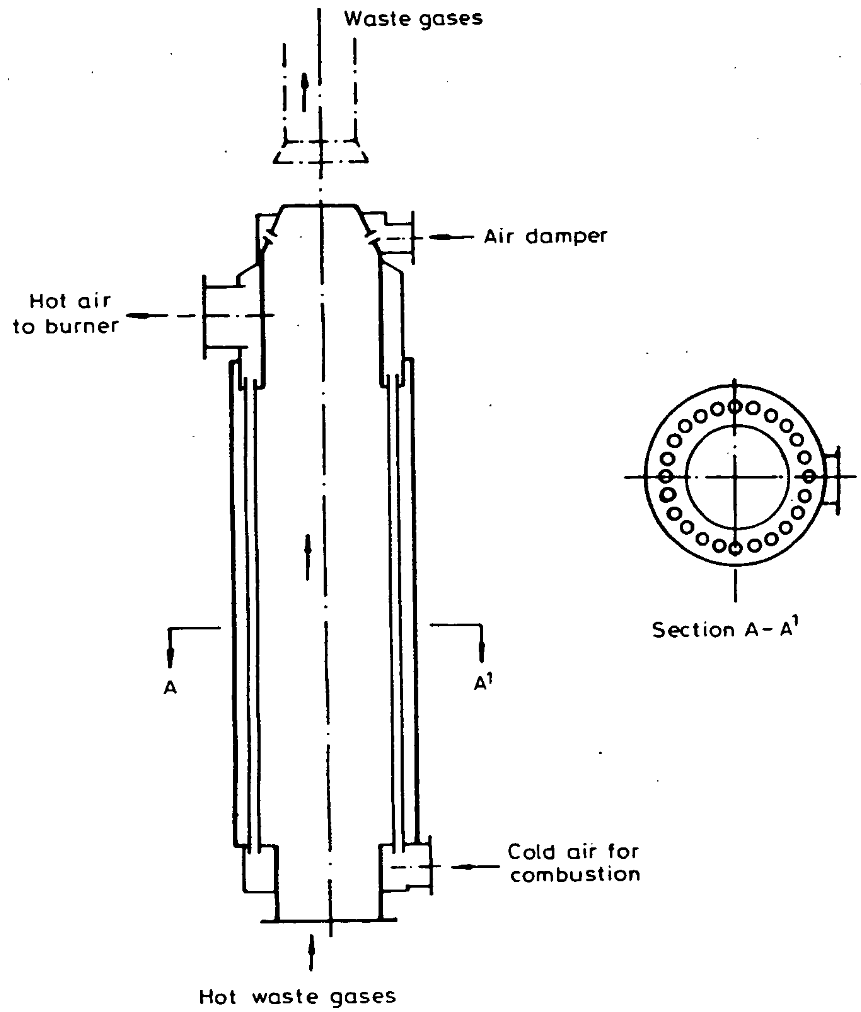

Fig. 4.15. The cage-type of recuperator. Cold air is preheated by passing it through pipes located inside the insulated (not shown) flue through which the waste gases pass.

that firing is from alternate sides, reversing every 20 min or so. Regenerative firing of furnaces is a well-established principle in the glass industry in general and is, indeed, more widely used than recuperative firing, especially for very large furnaces. It was generally believed to be unsuitable for E glass furnaces because of corrosion problems arising with available refractories. However, some glass manufacturers of wide experience who have added E glass to their range

of other glass products, have reported good results and, on occasions, fewer problems than they had encountered with metal recuperators.

Waste gases discharged from metal recuperators as currently used are at temperatures of 600–700°C and carry volatile pollutants like fluorides, boric oxide, sulphur and nitrogen oxides and dust. The residual energy can be recovered by installation of a waste heat boiler in which this energy is converted into steam which can then be used in a number of ways. In most countries, the pollutants must now be removed from the flue gases before they can be discharged into the atmosphere (see Section 4.5.9).

Another method of secondary heat recovery is to pass the waste gases, after their passage through the recuperator, upwards through the pelletised batch and thereby preheat the batch [22]. At the same time, a proportion of the boric oxide and fluoride pollutants can be removed from the waste gases, especially if alkaline earth oxides or carbonates are introduced separately into the stream of waste gases. It is claimed that up to 35% of the boric oxide and up to 20% of fluorides in the waste gases can be removed and recycled into the melting process by this technique [23].

(5) Water.

Water is required in conjunction with the operation of the melter for the following purposes:

(a) cooling the hot end of the batch feeder (and separate waste glass feeder, if used) as these are exposed to the furnace atmosphere;
(b) cooling the level control sensor (if necessary);
(c) cooling of water boxes or water pipes which will back up the glass contact refractories later in a campaign when they begin to fail (see Section 4.7.2.1);
(d) stopping of small glass leaks which may develop later in the campaign by playing a jet of water onto the leak;
(e) supplying emergency water in case of furnace failure by breakthrough of floor or sidewall tank blocks, or controlled tapping of furnace at the end of a campaign;
(f) cooling of instrument air compressors and after-coolers: and
(g) in hot climates, the cooling of LPG tanks, if used.

The above are all supplied by unpurified local water. (a)–(c) are supplied through a circulating closed-circuit system, the reserve storage tank of which is big enough to function as an emergency flow-through water supply. A typical system is shown in fig. 4.16. The corrosion of the batch charger tubes by fluorides in the furnace atmosphere can be minimised by allowing the cooling water to operate at a temperature of about 80°C as this reduces the rate of condensation. The flow is best adjusted manually by a valve in the supply line to the water-cooled tubes themselves, and which is set in conjunction with an indicating thermometer located in the outlet pipe from the tubes.

The system can be combined with the cooling water system for bushings but, in this case, the cooling water must be soft and filtered water.

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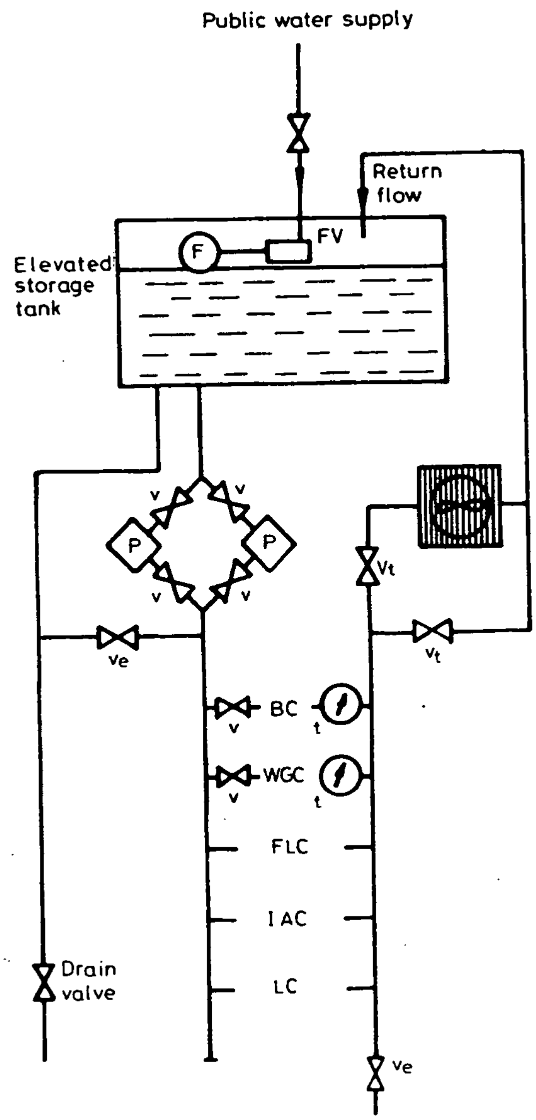

Fig. 4.16. Schematic drawing of melter cooling water system with examples of connected services. Legend: BC: batchcharger. F: float. FV: floatvalve. FLC: flux line cooling. IAC: instrument air compressor and after-cooler. LC: level controller. P: pump. t: thermometer. v: valve. v_e: emergency valve which opens should both pumps fail. V_t: temperature-activated valves to control temperature of water flow. and WGC: waste glass charger.

For cooling the water on the return side, a number of systems are available depending on plant location, weather conditions, and availability and cost of water. Whichever means is used for cooling, it is highly desirable that the cooling water itself remains in a closed system as this avoids contamination, growth of algae leading to pipe blockage, etc.

4.5.7. *Instrumentation, controls and alarms*

For a glass fibre plant to operate successfully it is necessary to aim, and largely achieve, constant operating conditions. As far as the production of fibre is concerned this can only be achieved if the quality and properties of the glass are near perfect and constant. Hence as many factors as possible that could influence the properties of the glass, e.g. the viscosity, are automatically controlled directly or indirectly by the use of suitable instrumentation.

All instrumentation as well as PLC's, motor starters, indicating lights and alarms as well as closed-circuit television, if used, are located in an air-conditioned control room which forms the headquarters of the direct-melt fibre forming operation.

(1) Automatic controls.

(a) Temperature. Temparatures are measured by Pt/13%Rh·Pt thermocouples protected by 10%Rh·90%Pt sheaths. The melter temperature is taken just below the crown above the hot spot, and is automatically coupled to the burner system. The burners themselves are preset to give adequate fusing of the raw material by the time they reach the hot spot and (downstream) bubbler zone, and they respond proportionately to the temperature controller. The temperature profile down the length of the furnace is set manually by adjusting burners; once set, the automatic control adjusts all burners simultaneously and proportionately via the control thermocouple.

(b) Recuperator air temperature. This must be constant at about 700°C to achieve a constant melter temperature and constant flame conditions. A spill air control is part of the system so that, should the secondary air temperature rise to that approaching danger for the recuperator as such, more air is pumped into the preheating annulus or pipes of the recuperator, some of which is then spilled.

(c) Fuel/air ratio. It is important for glass quality that glass melting takes place under conditions of a small but constant excess oxygen content of the flue gases. This excess oxygen content should be maintained within narrow limits. This is achieved by coupling an automatic excess oxygen analyser to the fuel/air ratio controller. Of these, the Corhart Oxygen Sensor is typical. It consists of a ceramic tube with both its inner and outer surfaces coated with platinum, a compensating thermocouple, and a ahead for connections to sensor and thermocouple. This assembly is mounted horizontally through the wall of the furnace into the path of the flue gases.

The sensor produces a voltage which is a function of the relative difference

in oxygen concentration between its outer (furnace) atmosphere and inner (ambient air) surfaces and the temperature at which the sensor operates. This output voltage is given by

$$E = 0.0215 \times T \log_e \frac{O_2 \text{ (reference)}}{O_2 \text{ (furnace)}}$$

where E is the sensor output in millivolts; T is the sensor operating temperature in degrees Kelvin; O_2 (reference) is the oxygen concentration of air in percent (20.9); and O_2 (furnace) is the oxygen concentration in the furnace gases.

This sensor will operate satisfactorily for long periods in normal furnace atmospheres between 600°and 1600°C and can be linked to automatic combustion control systems which permit the trimming of the excess oxygen content of flue gases to very small but constant amounts, thus saving fuel and creating stable atmospheric conditions in the furnace.

(d) Furnace pressure. Since the furnace is not a gas-tight structure it is important to prevent cold air from being sucked into the combustion chamber. For this reason the pressure is adjusted so that, at glass level, it is atmospheric. This means that, at about 50 mm above the glass level, it is 1.75 mm w.g. The pressure is controlled by means of an air damper, which operates by pumping cold air into the chimney above the recuperator thereby restricting the outflow of flue gases from the furnace.

(e) Glass level. Apart from the effect that a varying glass level can have on the productivity and fineness of glass fibre produced, glass quality itself requires that the glass level be maintained within tight tolerances, i.e. within 0.5 mm. The level itself is usually detected in the forehearth beyond the outlet from the melter by one of many level detectors/controllers. The signal obtained is used to control the rate of batch feeding into the melter as well as for providing a printed record of changes in glass level.

(2) Indicating measurements supplementary to the controls.

(a) Temperature. The temperature conditions in a melter are not defined by the measurement and control via a single thermocouple. For this reason three or more are installed along the centre line of the crown; in addition, several thermocouples are immersed in the glass by insertion upwards through the floor of the furnace along its centre line. Temperature measurements are taken in line with the batch feeder, in the area of the bubblers, plus one midway between these two, plus one, most important, near or under the skimmer block. These temperatures can be recorded on a multipoint temperature recorder, but it is very difficult to analyse what is going on from this data alone. It is best to take the temperature reading of each of these thermocouples and plot these against time in parallel with the temperature readings of thermocouples under the crown. It has been suggested more than once that the whole melting process of E glass can be controlled

by controlling the temperature near or under the skimmer. There is some truth in this, but it must be remembered that the times needed for this thermocouple to react is long, and the process as a whole, both short-term and longer-term must be clearly understood for this philosophy to apply. It can however be said that, if the temperature of this thermocouple stays constant, then the quality of the glass stays constant; if it changes, then changes to the operating parameters of bushings located downstream will become apparent and may call for corrective action.

Once the process is fully understood, control of the glass melting operation is best done by computer.

(b) Air flow through bubblers. Bubblers adjacent to the side wall use about 0.2 m^3 of air per hour, the others 0.25 m^3/h. The flow is controlled by pressure regulators in conjunction with a needle valve and visual flow meters.

(3) Operational indicators.

Motor starters and switches for the following equipment and light indicators to show what equipment is in operation are also located in the furnace control room:

(a) Combustion air fans and primary air compressors, if used.
(b) Oil pumps and line heaters and/or gas compressors.
(c) Cooling water system.
  (i) Pumps.
  (ii) Cooling radiator fans, if used.
(d) Batch feeder(s).
(e) Instrument air compressors, if used.

In addition, it is useful to have a level indicator for water in the reserve tank. In addition, all water temperature indicators installed at entries and exits of equipment, e.g. batch feeder tubes, should be located in the control room, and the readings should be periodically recorded.

(4) Warning alarms.

Certain failures will require immediate attention. If and when they occur, they should set off a flashing light and alarms audible inside and outside the control room; for obvious reasons the furnace controller should be able to switch these off and reset them. The following events should be covered:

(a) Electric power failure lasting longer than 5 s.
(b) Mechanical failure of either combustion air fan, or primary air compressor, if used.
(c) Failure of gas compressor.
(d) Overheating of recuperator.
(e) Failure of batch feeder.
(f) Low level of batch in batch feeder surge hopper or silo.
(g) Reduction of pressure in cooling water system.
(h) Dangerously low level in cooling water tank.

(i) Reduction of pressure in oil line and/or reduction in pressure in gasline downstream from compressor

All the above automatic and indicating controls, together with motor starters, indicating and warning lights, and alarms, cover the operation of the melter. To these should be added similar controls which govern the remainder of the total furnace operation, i.e. the forehearth system, and the controls for the fibre-forming furnaces (bushings), if desired. These will be discussed later.

4.5.8. New developments covering furnaces for the manufacture of E glass

The high cost of energy has forced all users not only to make maximum use of the energy consumed, but also to consider what steps could be taken in the future to use it more efficiently. A fossil-fuel-fired furnace is inherently a most inefficient machine; for E glass manufacture it is even more inefficient because of the extra melting area and high melting temperatures required for this type of glass. An optimistic estimate indicates that at least 70% of the energy supplied to an E glass unit melter is wasted, even with the benefit of a recuperator. As a furnace ages, the energy wastage increases. Since heat losses occur through walls, roof, and floor, in addition to via the waste gases, the following steps obviously improve fuel efficiency:

(1) improve the insulation of the furnace wherever possible;
(2) keep excess oxygen in the waste gases to a minimum;
(3) operate at maximum glass output; the marginal input of energy per extra kg of glass is insignificant since the heat losses are virtually constant for a given size of furnace;
(4) reduce the number of furnaces in a plant to operate, as far as technological factors permit, the largest possible furnace(s); and
(5) make use of energy remaining in the waste gases after passing through the recuperator by installing a waste heat boiler.

(3) and (4) present serious commercial problems because, although obviously true, if the output of furnaces operating at maximum output cannot be sold, then the excercise is purely academic and useless and can be financially ruinous. It would be better to operate a smaller furnace to capacity and sell all production, even if some market opportunities are missed, than operate a larger furnace and have spare capacity.

The above considerations apply whatever the size of furnace being used. However, the energy efficiency of furnaces is constantly being improved by changes in design concepts. These are based on electric melting which, although already widely used in other parts of the glass industry, has been slow to be applied to the manufacture of E glass, and for good reasons:

(1) E glass, having a negligible alkali content, has a high electrical resistance and ionic conduction necessary for electric melting can take place only at comparatively high temperatures; and

(2) at these high temperatures, the refractory required for E glass to give glass of good quality, namely dense chrome oxide, has a higher conductivity than the glass itself, creating the danger that a substantial proportion of the electricity could be conducted through the surface of the refractory rather than through the glass. Under these conditions the refractories are rapidly destroyed, and the quality of the glass melted is poor, if not useless, as a result of refractory contamination.

However, it is worth considering what progress has been made and what potential exists.

4.5.8.1. *All-electric furnaces*

It can be readily appreciated that heating a bath of glass by radiation from flames and/or refractories above the bath must be less efficient than if the heating could be done within the bath of glass itself. The efficiency would be improved further if the bath of molten glass could be insulated on all sides including the top surface. All-electric furnaces suitable for wide variety of glasses in fact operate just in this fashion, with well-insulated side walls and bottom and the top surface permanently covered with unmelted batch. This unmelted batch fulfills two functions: first, it insulates the surface of molten glass against heat losses and, second, it serves as a cold zone in which volatile components, like B_2O_3, can condense and thus eliminate both waste and pollution from this source.

Of all the types of electric furnaces in existence, the original Elemelt furnace with plate electrodes inserted through the side walls was tried for E glass manufacture more than once but failed because the refractories which could be used under these conditions failed too quickly, leading to short furnace campaigns and poor quality glass.

The design shown in fig. 4.17 is a valid concept since the electrode lay-out and connections specifically attack the problem of shielding the side walls from stray currents by placing a ring of earthed electrodes around the 'working' electrodes [24].

The author is not aware whether any all-electric furnace of the above type is actually in use anywhere. It seems unlikely in view of the fact that unit melter operations are now well-established and are very suitable for the larger scale operations now becoming normal (150–200 tons/day of glass); in many of the more sophisticated plants fossil-fuel firing has been augmented by electric heating (boosting), as will be discussed later.

However there is one all-electric furnace of a totally different type which is used under conditions of cheap electricity supplies or where the tonnages required are small. This is the Pochet furnace.

The basic concept of the Pochet furnace [25, 26] is that the problem of refractory corrosion can be avoided by melting the glass in frozen glass of its own composition. If this theory had been taken to its extreme, i.e. a water-cooled metal container was used as the surface against which some E glass is frozen, this would cause

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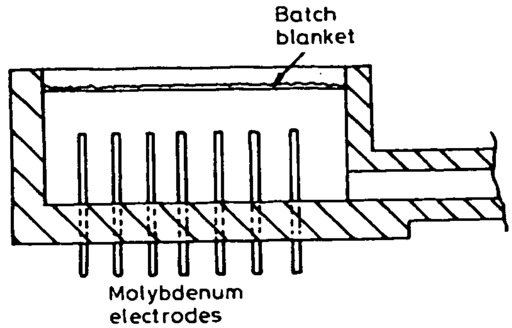

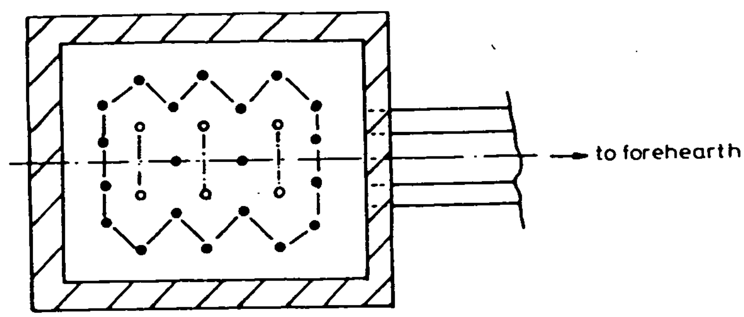

Fig. 4.17. Suggested arrangement of electrodes to effectively shield the refractories from electric currents passing along their surfaces by interposing a ring of earthed electrodes.

an excessive loss of energy into the cooling water. In practice, therefore, a water-cooled bowl is used which is lined with refractory about 50–75 mm thick to act as a radiation shield. The furnace therefore consists of a bowl, usually of copper, 2 or 2.5 m in diameter and about 0.5–0.75 m deep to which a series of parallel pipes have been soldered on the outside to provide the water cooling. Heating is by means of three electrodes in the centre grouped symmetrically around an outflow pipe the entry to which is located only 10–20 cm below the glass surface (fig. 4.18). The glass in contact the refractory lining is of such high viscosity that the rate of corrosion is slow. Thus, the life of refractories can be made to balance the life of the electrodes. The refractories used are high quality alumina, although, in more recent cases, the top ring of refractories has been replaced by chrome-zircon refractories of good thermal shock resistance and better resistance to corrosion by melting batch.

The principles of operation are straightforward: the lined copper bowl is mounted

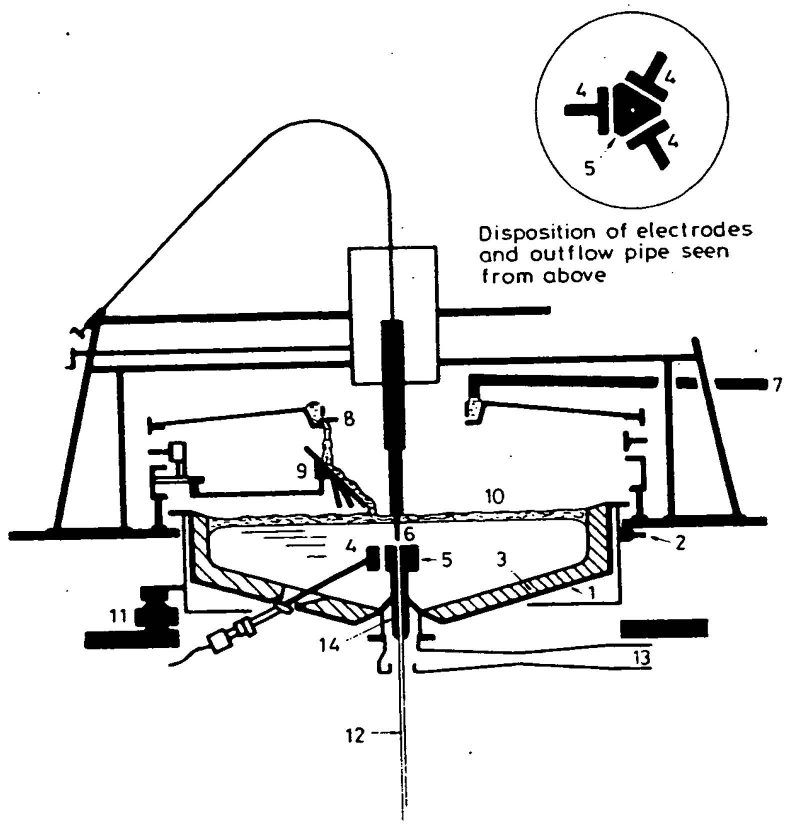

Fig. 4.18. Principle of operation of Pochet furnace. 1. Copper bowl surrounded by water-cooled pipes. 2. Cooling water inlets and outlets. 3. Refractory radiation shield. 4. Electrodes and 5. Glass outflow pipe. all of molybdenum. 6. Glass flow control rod. also of molybdenum. 7. Batch supply. 8. Rotating batch feeder. 9. Reciprocating batch distributor. 10. Permanent batch blanket. 11. Load cell: the other two legs (not shown) are on hinges. 12. Glass stream. 13. Exhaust duct for steam created by burning 14. Hydrogen blanket shielding exit of molybdenum pipe.

on two hinged supports and one load cell. the function of which is to control the weight of the furnace with the glass and batch it contains. Heating is via three molybdenum electrodes, each consisting of a shaft and a head. and each connected to one phase of a three-phase power supply: the electrodes encircle an outflow pipe which is electrically neutral. The furnace operates at very high melting temperatures. i.e. in the vicinity of the electrodes the temperature reaches 1900–2000°C thereby achieving very high melting rates and setting up rapid upward convection currents between the electrodes and the outflow pipe. Some of this very hot glass is withdrawn through the outflow pipe. the rate of flow being controlled by a molyb-

denum rod inserted into its upper section. The life of the electrodes is about 4 months.

The glass leaves the outflow pipe at the base of the furnace; in order to protect the exposed end of the outflow pipe it is surrounded by a hydrogen flame and an extracting duct to remove the water vapour so created.

On exiting, the outflow pipe the glass is at a temperature of about 1550–1600°C and falls into the conditioning section of a forehearth. Some companies made the stream cool first on an inclined platinum-rhodium trough from which it flowed into the forehearth, but most now permit the stream to fall 1–1.25 m into an open-top extension of the forehearth. As the glass stream enters, the momentum of the stream gives very effective stirring to the glass . For details of the forehearth and its functions, see Section 4.6.2. It is obviously desirable that the whole glassmaking operation of a Pochet melter and the transfer of the glass down the forehearth to the bushings is automatically controlled. This is particularly important as the small volume of glass which comprises the melter is highly sensitive to small changes and interruptions in supply, a situation which is outside the practical control of human beings. Thus the operation is best controlled automatically by three separate control loops:

(i) The glass level in the forehearth, controlled by any standard level sensor is linked to a motorised glass flow control rod moving inside the outflow pipe (see item 6 of fig. 4.18);
(ii) the load cell, indicating the weight of furnace plus glass and batch, actuates the power supply, low weight raises power and vice versa; and
(iii) a wide angle radiation pyrometer installed above the furnace and scanning the surface which should be covered with batch is linked to the batch feeder/distributor so that, by increasing or decreasing the rate of batch deposition, the total radiation is kept constant.

Figure 4.19 shows the three control loops in diagrammatic form. The voltage used for E glass is about 220–250; as the electrodes wear and the gap between electrode and outflow pipe increase, the voltage climbs: this calls for an adjustment to the electrode position which can be advanced by screw adjusters of the electrode holder.

Consumption of electric power is about 1.6 kW/kg of glass. Since the molten glass is permanently covered by batch, volatile losses are much reduced: B_2O_3 losses are 0–5% compared to 15–20% for a unit melter, and F_2 losses are about 15% compared to 50% for a unit melter.

The furnace is used in two sizes for production of E glass: a 2 m diameter furnace for a production of 7–8 tons of glass per day, and a 2.5 m diameter furnace for 12–14 tons/day. A larger 3 m diameter furnace is likely to be developed and soon can be envisaged to melt about 20 tons/day.

Details of furnace design are also being developed to aim for longer periods between electrode changes. The problem of electrode life is connected with their design: as they wear the head has to be advanced to maintain the correct voltage. when the head has worn away, the furnace has to be stopped for electrode replace-

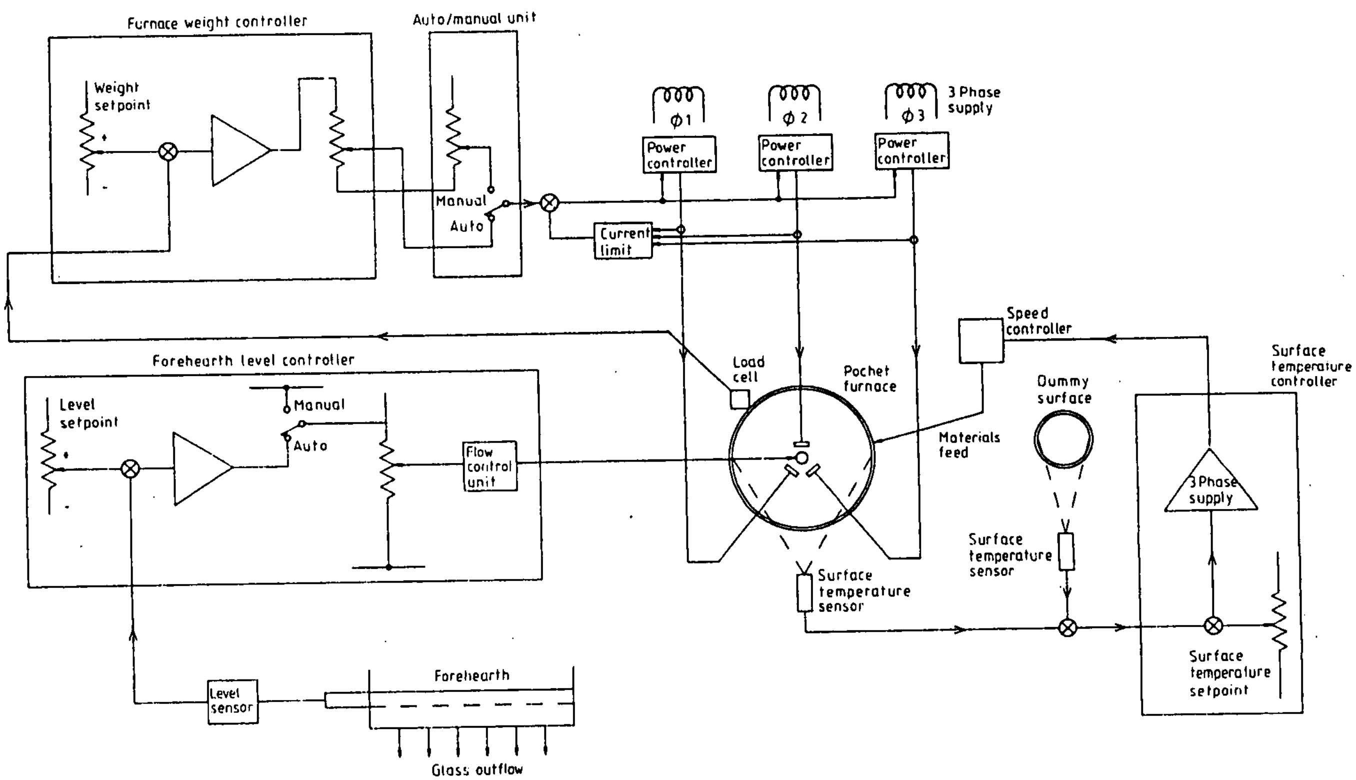

Fig. 4.19. Automatic control of Pochet furnace, showing the three control loops: glass level in forehearth to glass flow control rod, load cell to electric power, radiation from surface of melter to batch feeder. Depending on the spectrum of wavelengths sensed by the optical pyrometer, a second pyrometer focussed on a dummy surface covered with batch may, or may not be, required. (Courtesy: Eurotherm International plc, U.K.)

Fig. 4.19. Automatic control of Pochet furnace, showing the three control loops: glass level in forehearth to glass flow control rod, load cell to electric power, radiation from surface of melter to batch feeder. Depending on the spectrum of wavelengths sensed by the optical pyrometer, a second pyrometer focussed on a dummy surface covered with batch may, or may not be, required. (Courtesy: Eurotherm International plc, U.K.)

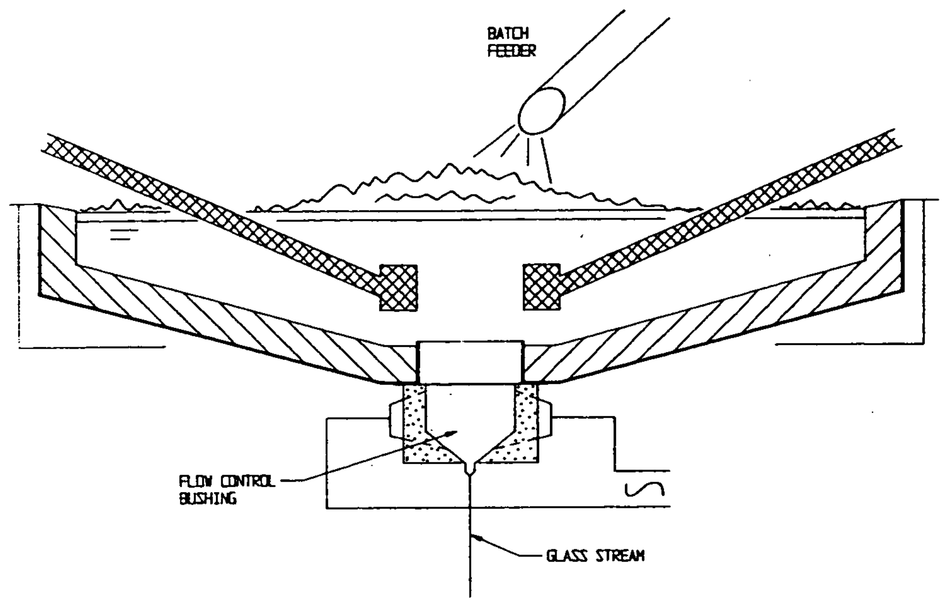

Fig. 4.20. Modified Pochet furnace with top-entry electrodes and glass flow control by means of a single-orifice platinum alloy bushing. In this case the level control of the forehearth is linked to the temperature controller of the bushing.

ment; at the same time, the head of the outflow pipe has also been corroded away. In electrically-heated furnaces normal in the glass industry, the electrodes are rods which, as they wear away at their hot ends, can be advanced, and as electrodes get shorter, new lengths of rod can be screwed in to the end of the old one, so that the operation is not limited by electrode life at all. This approach has led to two changes on Pochet furnaces:

(i) The outflow of glass, controlled in the region of highest glass temperature by a rod suspended inside the outflow pipe has been replaced by a molybdenum-lined passage through the refractory joined to a small platinum-metal furnace provided with a single outlet nozzle [27]. This single-nozzle bushing is encased in refractory and is heated separately by electricity similar to bushings for fibre forming (see Section 5.2). The flow is now controlled by raising or lowering the temperature of this flow control bushing (see fig. 4.20). This simplification has made the burning of hydrogen at the exit from the furnace obsolete.

(ii) The batch feeding system can be simplified once the flow control has been moved to the base of the melter by feeding the batch into the centre of the

furnace and allowing the thermal currents which move radially outwards from the centre to spread the batch over surface of the glass.

(iii) It then becomes possible to insert the electrodes from the top which makes changing them a relatively simple procedure and certainly does not entail the shutting down of the furnace. Each electrode consists of a water-cooled shaft to which a specially-shaped head is attached. Each electrode assembly is mounted on a sturdy carrier located in a slide fixed to the platform surrounding the furnace; the electrode is mounted on the carrier so that angular and vertical adjustment in the vertical plane is possible; in addition, the carrier can be advanced and retracted in the normal way so that distances between electrodes can be adjusted as the heads wear away. This new arrangement enables electrodes to be changed in a few minutes.

The life of a furnace is now governed by the need to replace refractory whenever the heat losses into the cooling water become excessive.

Comparisons between Pochet furnace and unit melter operations leads to the conclusion that the choice is a question of investment, the products to be manufactured, and the intended scale of the operation. The advantage of proceeding with a Pochet furnace is that one can start with a plant of only 2000 tons/year output of products, that one can advance by changes in downstream equipment to increase production (by changing to a larger furnace) without major investment, or if demand increases further, by installing a new and separate line. For the same plant output, the investment required for a plant based on a Pochet furnace is significantly lower than is the case for a unit melter, especially if much of the equipment (furnace, refractories, electrics, etc.) can be manufactured in the country in which it is to be installed. The drawbacks are that fibre of 7 μm or under cannot be made satisfactorily; this may not be of major import. Also, the supervision and control of the furnace and its associated operations, because of its small volume, is more critical but this can largely be taken care of by automatic control. Lastly, the operation, especially those without the recent improvements mentioned above, can be subject to relatively frequent shut-downs for electrode and refractory replacement which involves time losses and downgrading of product quality during the re-establishment of controlled production conditions.

A 2 m diameter Pochet furnace weighs under 5 tons and a 2.5 m furnace about 10 tons. This type of furnace can therefore be erected on a trolley together with its bus bars and all utility connections. When a furnace has to be shut down, it is then possible to effect a turnround glass-to-glass in about 12 h. This involves rapid cooling of the old furnace, wheeling it out on its frame, wheeling in a spare furnace, connecting up, lighting up and restarting the glass flow into the forehearth. The only extra investment would have been a spare bowl, the utility connections and the trolley for carrying the furnace.

4.5.8.2. Mixed electric/fossil fuel-fired furnaces

The use of furnaces of this type is spreading, especially for larger furnaces; they are referred to as 'furnaces with electric boosting'. This furnace looks like a fuel-fired furnace, but is deeper and is provided with molybdenum rod electrodes coming up vertically through the floor (see fig. 4.21) [28]. As a result of the electric heating, sometimes located under the batch blanket, the specific melting area required is reduced to about 1.1–1.0 m^2/ton/day or, for very large furnaces to even lower figures. In addition, the temperature in the melting chamber above the glass can be reduced, and this reduction causes the loss of B_2O_3, fluoride and dust to be reduced also.

In an alternative version, the electrodes are installed downstream from the batch feeder where the upward current of hot glass accelerates the melting of the advancing edge of the batch and, further downstream assists in the refining and homogenisation of the glass.

The ratio of electrical to fossil-fuel energies is often quite small, e.g. 8–15%. However, the total specific energy consumption is only about 3000–3400 kcal/kg glass for a furnace of 30–35 tons/day output; this is about 30% lower in energy terms than the average for a totally fossil fuel-fired furnace.

It is believed that with some large manufacturers the ratio of electrical to fossil-fuel energy inputs reaches about 80%.

For details of installation, see W. Trier [20], page 214.

4.5.9. Control of atmospheric pollution caused by a unit melter making E glass

Atmospheric pollution from wholly or partly fossil fuel/air-fired unit melters making E glass originates from the following:

(1) Fluorides are evolved from fluoride-containing raw materials as well as, to a lesser extent, from the glass itself. Without electric boosting, the quantity of fluoride evolved approximately equals the quantity which enters the glass, i.e. half the fluoride which enters the furnace in the batch is lost into the atmosphere. The fluorides are evolved as hydrofluoric acid, hydrofluorosilicic acid and fluoborates.

(2) Boric oxide is evolved mainly from the raw materials and to a smaller extent from the glass itself. In a totally fossil fuel-fired unit melter, the losses can reach 20% of the amount fed into the furnace. The faster the glass is melted, i.e. the higher the pull (tons/day) of a given furnace, the lower the percentage of B_2O_3 lost. Some of the boric oxide vapour condenses in the cooler parts of the furnace; the remainder forms a white plume of boric oxide smoke on leaving the furnace chimney.

(3) Batch dust from the fine raw materials which are carried out of the melter in the waste gases.

(4) Sulphur oxides which originate in the main from the sulphur in the (oil) fuel and to a lesser extent, from sodium sulphate usually added to the batch to

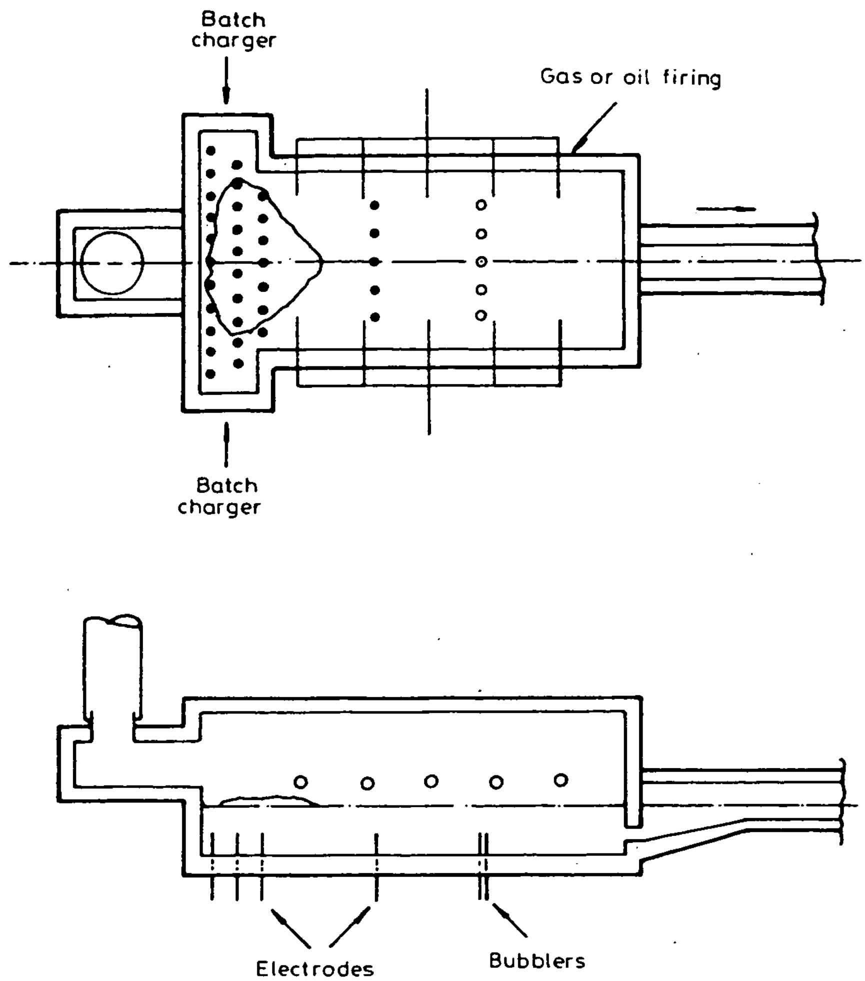

Fig. 4.21. Schematic drawing of a fossil fuel-fired unit melter boosted by electric heating. This provides a higher melting rate, lower operating temperature, lower energy consumption, and lower losses of volatile components compared to the solely fossil fuel-fired unit melter.

assist in dissolving remnants of undissolved silica and traces of sulphates in the raw materials.

(5) Nitrogen oxides which arise from the use of air for combustion.

The permitted levels of discharge vary from country to country but, for purposes of discussion, the German TA Luft standard can be taken as a basis of the degree of purification required. They are:

fluoride	5	$\mu g/m^3$ of gases discharged
sulphur oxides	1800	"
nitrogen oxides	1800	"
dust	50	"
boric oxide	10%	opacity

Measurements of pollution levels are taken in the flue itself prior to discharge to the atmosphere.

Compliance with legal requirements covering pollution levels must be studied separately for each case and includes such factors as

- the scale of the glassmaking operation since this governs the rate at which pollutants are created;
- the applicable laws and regulations governing permitted pollution levels, now and in the foreseeable future; and
- the local climate, possibility of inversions, prevailing wind direction, etc.

There are no technical problems in meeting the legal requirements for control of pollution; it is simply a question of investment and operating costs. Broadly speaking, pollution control, other than the simple and now inadequate provision of a chimney of sufficient height, fall into two groups: the wet process, and the dry process.

The wet process involves the use of a gas scrubber in which the waste gases, after leaving the recuperator of the melter, pass upwards through a tower provided with impingement plates at which water flowing downwards meets the gases flowing upwards. Extremely close gas–liquid contact can be achieved which causes gaseous pollutants to dissolve in the water and solid pollutants to be held in the water. This now contaminated liquid can be recirculated many times through the tower so that make-up water is a very small proportion of the water circulating. The contaminated liquid is purified by the addition of hydrated lime which precipitates calcium fluoride and sulphate; the precipitated matter includes batch dust. After allowing the solids to settle out, the supernatant liquid can be re-used in the scrubber process: the solids, in the form of a sludge, are removed and dumped.

In an alternative system a dilute suspension of hydrated lime in water is injected into the hot gas stream to both cool gases and neutralise and precipitate the pollutants. This suspension can be circulated many times before the resulting calcium sulphates and fluorides together with any boric acid and dust are carried forward as small particles to be collected in a filter system.

There are at least two dry processes. In the Artec System, developed in Japan especially for the glass industry, the waste gases are first cooled by passing them through a chamber in which a controlled quantity of water is injected as a fine mist to cool the gases to a temperatures acceptable to filter bags. The cooled gases are then brought into contact with very finely powdered slaked lime which reacts with both fluorides and sulphur oxides to form solid fluoride and sulphate. The gases, which now contain the pollutants in solid form together with batch dust carried over from the melter, are passed through bag filters which collect all solid matter. The materials are, in many cases, suitable for return into the glassmaking process. The cleaned waste gases are then discharged into the atmosphere.

An alternative dry process is the R-C Teller system, widely used in North America, Japan and Europe. It comprises three process stages:

(1) The hot waste gases from the furnace are subjected to sprays of calcium hydroxide slurry which not only cool the gases but react with acids encountered in them to form calcium salts in the form of small particles which are carried forward in the gas stream.
(2) A suitable powder is then injected and dispersed into this gas stream in a dry venturi, resulting in agglomeration of fine particles and secondary neutralisation of acid fluorides. Powders for injection are selected usually from locally available materials. In North America, nepheline syenite is used but many other minerals are suitable also.
(3) The treated gas stream passes to a bag filter system where the injected powder forms a crystalline coating on the bags, thereby reducing bag blinding, improving filtration efficiency, and providing continuing contact between pollutants and reagents.

By selecting suitable operating conditions at the various process stages, boron compounds can be separated from the gas stream and collected in the waste dust. As in other dry systems, the collected dust, if of suitable composition, can be used as a raw material for making E glass or other glasses [29].

Much of the pollution problem can be brought under control by the use of oxygen instead of air for combustion. This is a new technology which is providing interesting results which are beginning to be applied to the glass fibre industry.

Although special burners have to be used and facilities for storage or manufacture of oxygen on site have to be installed, it is beginning to look as if the capital cost of traditional fuel/air furnaces plus the necessary pollution control equipment will exceed that of a correctly designed fuel/oxygen furnace. The advantages of using oxygen instead of air are:

(i) the absence of nitrogen from the combustion process virtually eliminates the formation of nitrogen oxides;
(ii) the absence of nitrogen reduces the volume of combustion gases circulating in the furnace, thus reducing the amount of dust carry-over;
(iii) traditional recuperators or regenerators can be eliminated;

(iv) fuel savings in the region of 20–35% can be achieved; and
(v) the special burners designed for oxy/fuel firing achieve high flame luminosity radiating energy in the 1–2 μm wavelength range important for melting glasses, thus achieving higher melting rates [30, 31].

4.6. The forehearth or feeder

The forehearth or feeder is, as the latter description implies, a supply channel to allow the glass to flow from the melting furnace to machinery or equipment for converting the liquid glass into products of cold glass such as rods, tubing, containers, or fibres. Before any glass can be worked, however, it must be 'refined', i.e. it must become free of gas bubbles and become homogeneous both with respect to composition (freedom from cords or striae) and temperature. In most cases glass furnaces are provided with a separate section for refining and, originally, furnaces for E glass were provided with a refiner also. However, the low viscosity of E glass at the founding temperature and its acidic composition (i.e. its low alkali content) makes chemical homogenisation and evolution of gas bubbles easier, thus enabling the refining to be carried in the connecting channel between the melter and the working forehearth, i.e. the sections of forehearth from where marble making or fibre forming is carried out.

In the glass fibre industry, forehearths are used in the production of marbles (for remelting later and forming into fibres) or, in what is now more important industrially, for feeding liquid glass directly into fibre forming furnaces (called 'bushings'). The first section, i.e. the section between the melter and the forehearth sections to which bushings are attached, serves to refine the glass and condition it to the correct viscosity, i.e. temperature, for fibre forming. This section must be long enough to achieve refining and homogenisation to the working temperature. In the remaining sections of the forehearth the temperature should be held constant so that the glass is maintained at the correct viscosity for flow into the bushings attached to them.

The operation and control of the forehearth is completely separate from the melter although, of course, the two are physically linked at the entry to the forehearth, where the glass flows under the skimmer. In the case of marble manufacture, the forehearths tend to be short, ending often in two or four branches, each branch feeding one or a pair of marble machine. In the case of forehearths used in the direct conversion into fibre, the length of the forehearth is governed by the size and number of bushings that have to be operated and is, therefore, likely to be much longer. For purposes of heating and temperature control, these long forehearths are subdivided into separately controlled sections.

4.6.1. Forehearths for marbles manufacture

Marble machines have a production rate of about 4.5–5 tons/day of marbles about 21.5 mm in diameter. The temperature of the glass on leaving the forehearth is

about 1150°C. Each forehearth section leads to a given machine, or pair of machines, and is individually controlled for temperature.

Forehearth cross-sections have to be designed in relation to the flow of glass through them; in the case of marble manufacture they tend to be wider and deeper than those for the direct-melt process. Figure 4.22 gives a typical section of such a forehearth, and figs. 4.23 and 4.24 give two different layouts of forehearths for large furnaces. The glass leaves the forehearth through a specially designed orifice die which is lined with platinum alloy. The flow of glass is controlled by means of a plunger, also covered with platinum alloy where immersed in the glass: the position of the plunger can be adjusted to give the flow required, which, for a machine making 4.5 tons/day marbles of marbles is of the order of 200 kg/h.

Marbles are manufactured by placing a gob of glass of a given weight between two spirally grooved cylinders rotating in opposite directions, the rotational speed of the cylinder moving upwards in relation to the gob being slightly faster than the other cylinder. The grooves match in such a way that the glass marble rolls between the two cylinders as it is being formed and as it cools until it reaches their ends and drops onto a conveyor. Although most marbles now being made are about 21 mm in diameter, marbles of 25 mm are also known. For efficient conversion into fibres, control of marble diameter is important; the diameter is usually held to within ±1 mm. This means that the metering of the glass stream must also be accurately controlled. A common method is by means of a glass cutter illustrated in fig. 4.25. By this technique no glass is wasted, all of it being fed as gobs to one or other of the pairs of rollers of a double marble machine.

After the marbles have been formed they roll down a chute into a metal container, e.g. a 200 litre metal drum, in which they are collected and allowed to cool slowly for self-annealing; by this technique they are sufficiently stress-free and do not shatter on remelting. The need for cleanliness of the whole marble production operation, that is from the cutting of the glass stream to the packing of the cold marbles, cannot be overstressed. Dust and dirt interfere with the fibre forming process; also, oil and organic matter can damage the platinum metal of which the bushing is constructed. And no amount of washing and drying of dirty marbles will make such marbles be suitable for an efficient fibre forming operation.

4.6.2. Forehearths for the direct melt operation

The length of a forehearth for a direct-melt operation depends on the amount of glass is has to handle and the number of bushings attached for fibre forming. It consists of two basic sections:

(1) The first section is the refining and conditioning section designed to homogenise the glass and to adjust it to a temperature suitable for fibre forming; this section is usually 3–6 m in length.
(2) The second section simply serves to maintain the glass at this temperature and deliver it to the bushings for fibre forming. It can be of considerable length

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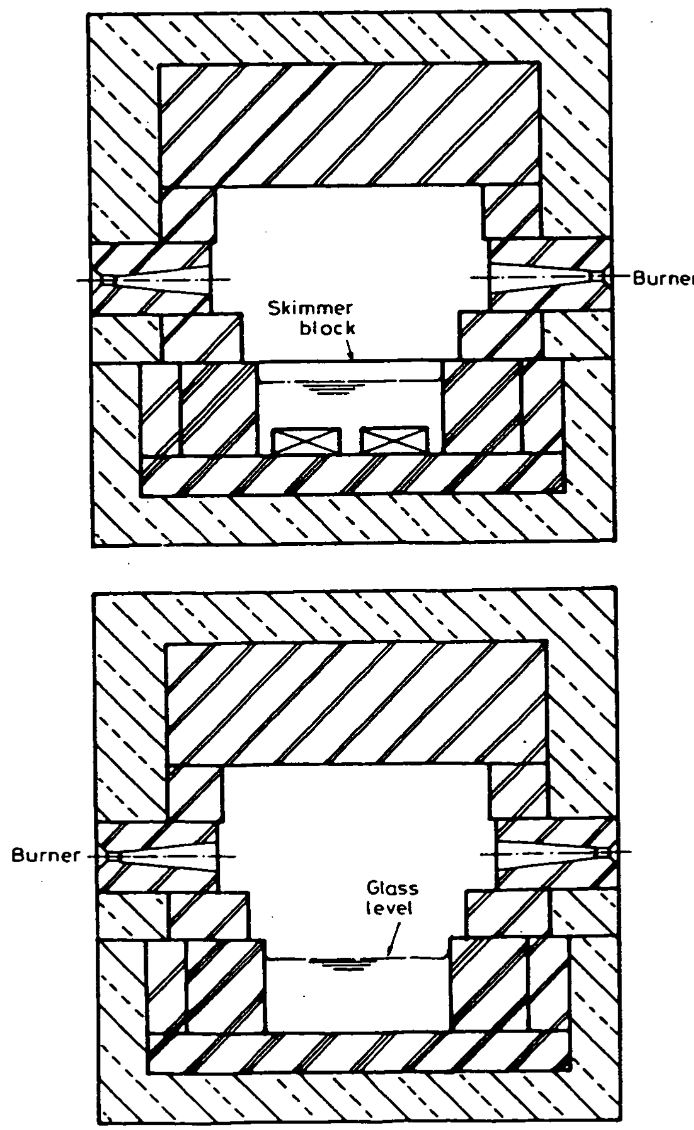


Fig. 4.22. Typical cross-section of forehearths supplying glass to marble machines. The upper figure includes a skimmer block. For code of refractories, see fig. 4.4. For scale, overall width about 1120 mm.

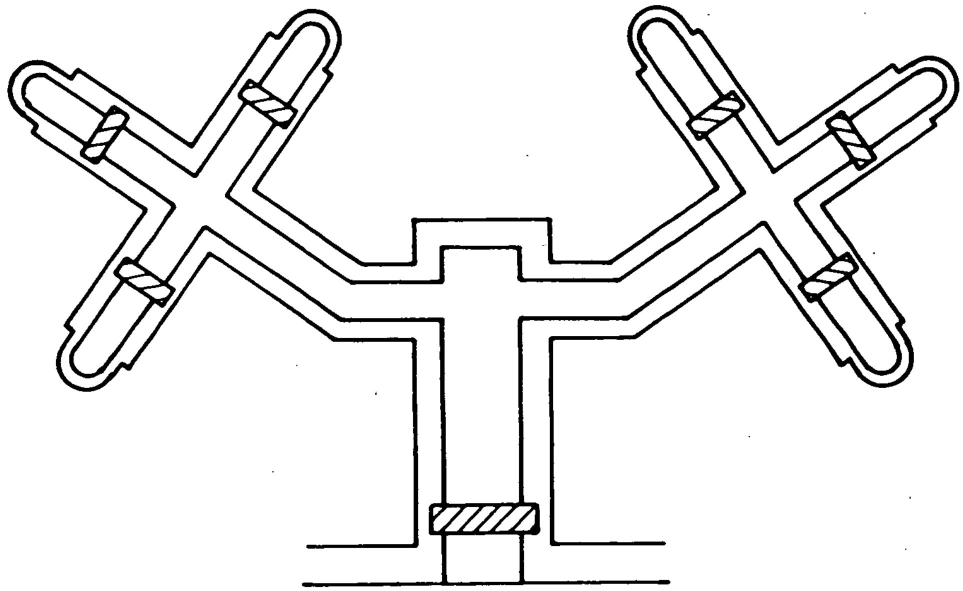


Fig. 4.23. Forehearth for marble manufacture. An example to supply six machine positions, one at the end of each limb.

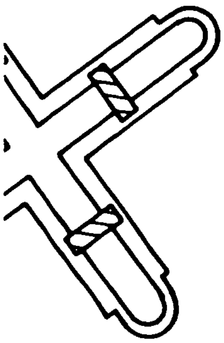
although, in recent years, it has tended to become shorter as a result of high-throughput bushings coming into use (see Section 5.2.4.): although each of these requires more space, they also have a significantly higher rate of fibre production.

As will be shown in Section 5.7.3, the distance between bushings can vary from 500–1220 mm and depends on the size of the bushing, location and size of auxiliary equipment and need for access for operation and maintenance. The average distance is, perhaps about 950 mm. Since a furnace of, say, 20 tons/day output and manufacturing an average mix of products might have to install 20–30 bushings, the total length of sections of forehearth holding bushings could be about 25–30 m.

When the two sections are added together you have a forehearth of about 30–36 m in length.

4.6.2.1. Configurations for forehearths

(1) The simplest arrangement is a straightline forehearth in which the sections for conditioning and fibre forming are in one straight line. In small operations of up to, say, 7–10 tons/day of glass such a forehearth is quite feasible. Figure 4.26 shows a schematic for such a forehearth when used with a Pochet furnace: it can accommodate up to about 16 bushings. For control purposes, it should



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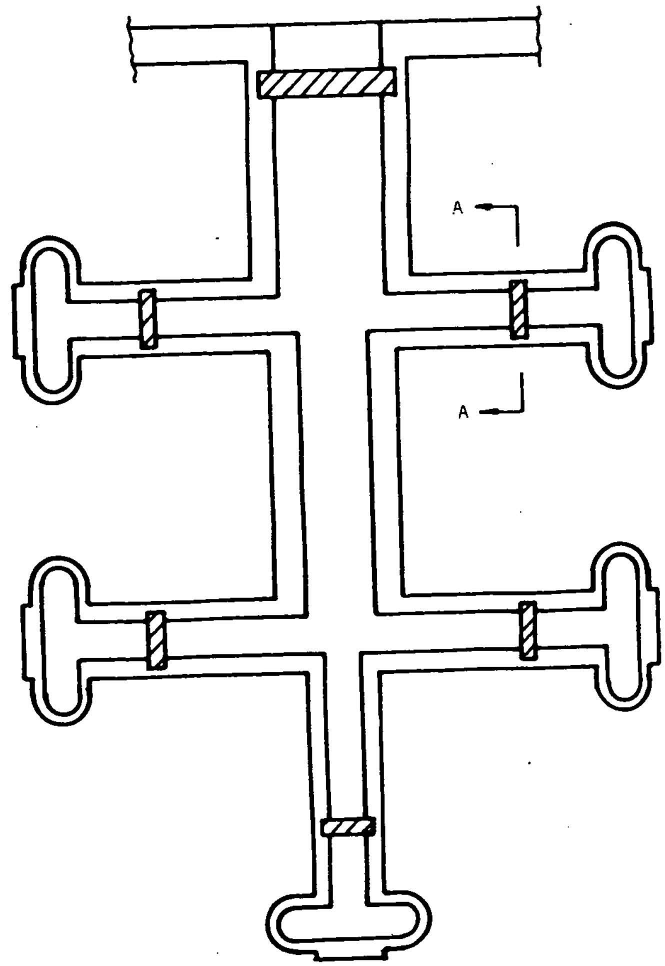


Fig. 4.24. Forehearth for marble manufacture. An example to supply 10 machines, two at the end of each limb. The cross-section shown in fig. 4.22 (upper) would correspond to section A–A indicated above.

be divided into four zones, one for refining/conditioning. and three for fibre forming.

(2) A 'T'-shaped forehearth layout is the best in principle (see fig. 4.27). Since Section A has to pass twice the quantity of glass when compared to Sections B and C, it is wider and deeper. If the number of bushings does not exceed 2 × 7, then each section can be controlled separately for temperature; if the number

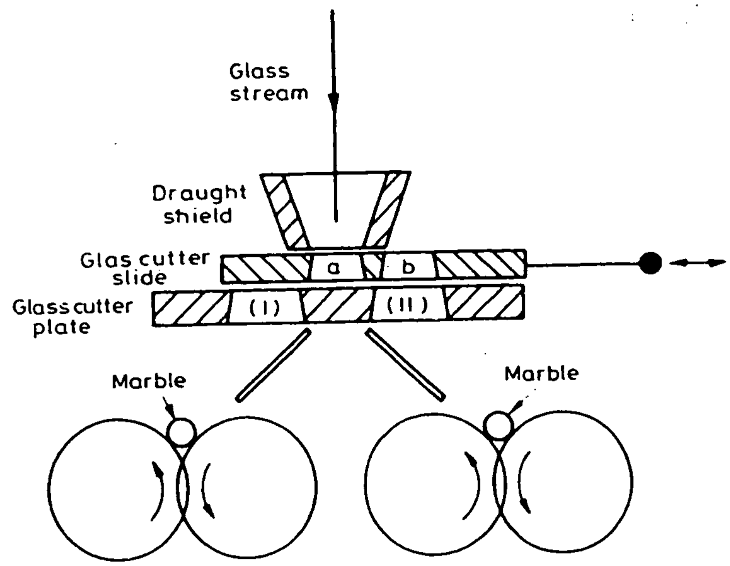


Fig. 4.25. Principle of operation of glass cutter used in marble manufacture. While slide is in position shown, glass flows into ring (a): after a preset time, the slide moves to the left so that (a) is above (i) allowing the gob of glass to fall through ring (i) onto the left pair of marble rollers. At the same time, glass is being collected in (b) which, on indexing, will reach the right pair of rollers.

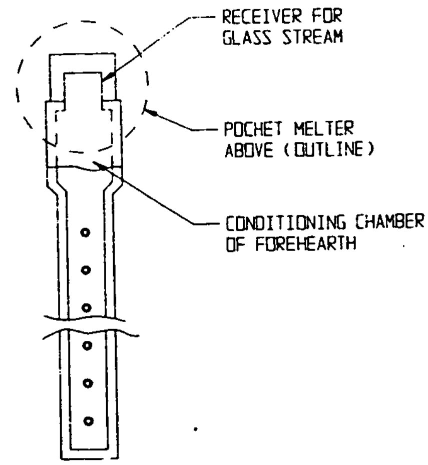


Fig. 4.26. Straightline forehearth used with small unit melters or Pochet melters of 7–10 tons/day output. Each dot represents one bushing at distance of 900–1100 mm apart. The example shown here is used with a Pochet melter. If used in conjunction with a unit melter, the transfer of glass is as shown in figs. 4.2 and 4.8.

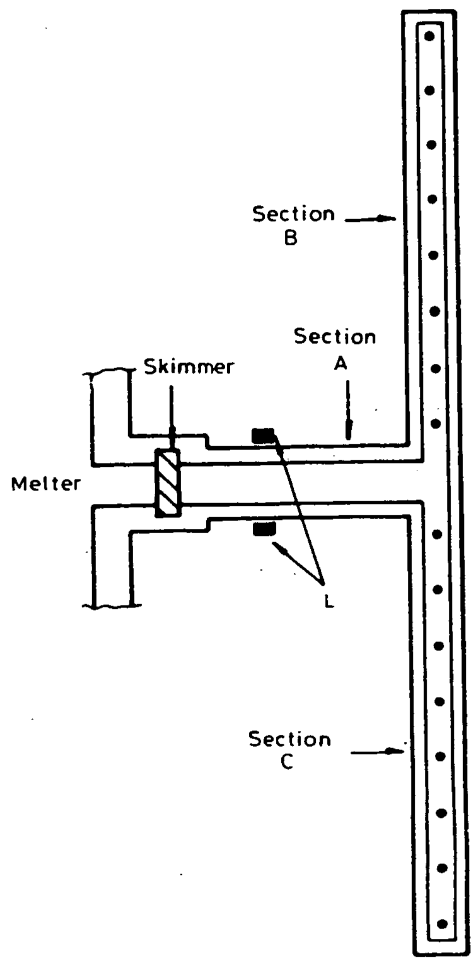


Fig. 4.27. A 'T'-shaped forehearth, probably the most popular from the point of view of the working environment. Also indicated is the location of an atomic radiation level controller; if not used, the glass level is measured by other means at the same location.

is greater than Sections B and C should each be divided into zones of 6 or 7 bushings each for purposes of control.

(3) For larger furnaces calling for forehearth with a large number of bushings, an 'H'-shaped forehearth layout has been favoured. There has been much debate on whether to have a 'T' or an 'H' configuration. The 'H' type fitted into the philosophy of creating a totally enclosed room for the fibre forming department, with the working areas of operators between opposing limbs of the forehearth.

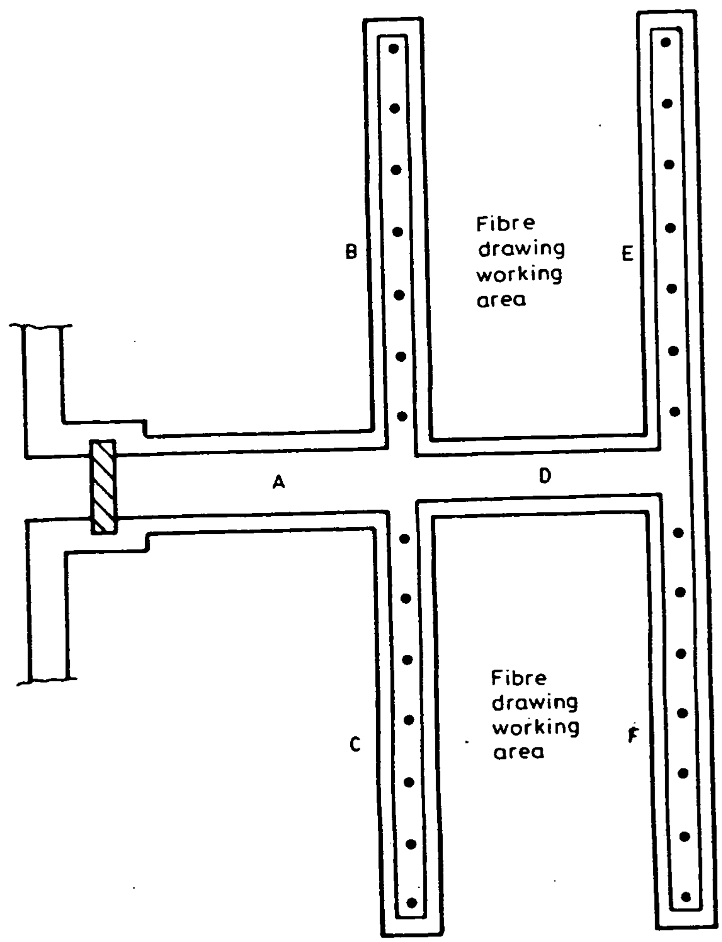
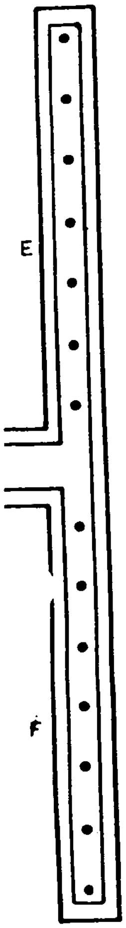


Fig. 4.28. An 'H'-shaped forehearth. The working area of the fibre forming department lies between the bushing forehearths.

However, provided the airflow around the fibre forming equipment is controlled to provide clean air moving in a downwards direction then there is no need for total enclosure and you can have an open plan, where there is open space behind operators operating from the side opposite Section A of the forehearth (fig. 4.28); this is much to be preferred from the point of view of 'human engineering'. As to the lengths of the forehearth sections, plants with 2 × 24 bushings in one line from one melter are known: in this case it is necessary to widen the upstream part of each limb in order to provide sufficient glass flow (fig. 4.29). Each section may also have to be made to slope slightly downwards to assist the flow of glass. Also, for



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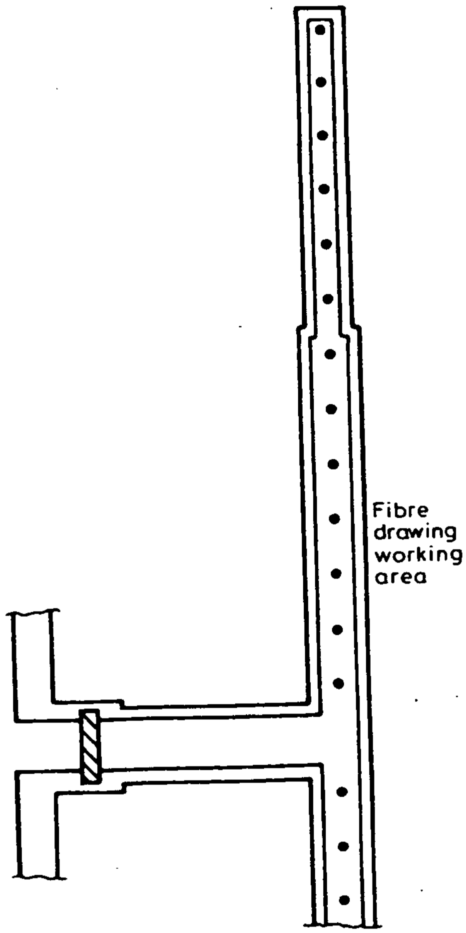

Fig. 4.29. A 'T'-shaped forehearth used with melters of up to 30 tons/day output. The upstream section of each limb is widened to ensure an adequate glass supply to the downstream section. The fibre forming department lies to the right of the 'T'.

purposes of temperature control, each section should be subdivided into zones of, for example, 6 bushings each.

Forehearths attached to very large furnaces, i.e. 120–180 tons/day, are usually of the type shown in fig. 4.30. This layout enables the tightest temperature controls to be achieved since each section is provided with only 5 or 6 bushings which constitutes one temperature control zone.

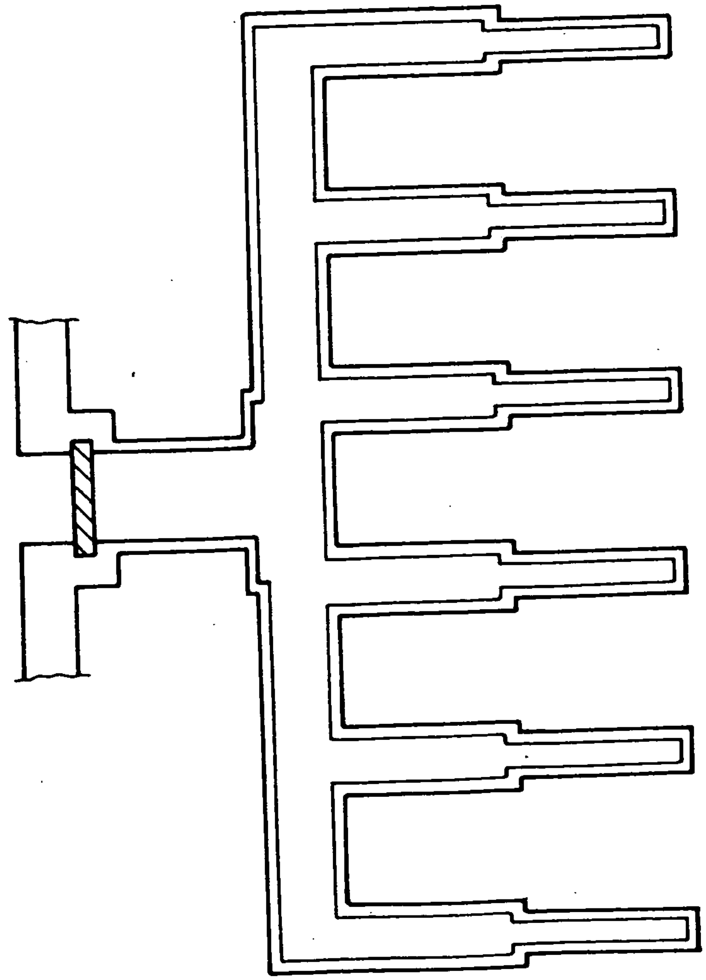

Fig. 4.30. Forehearth layout used with the largest melters. Bushings and fibre forming equipment are located under a multiplicity (six shown here) of parallel forehearth limbs.

4.6.2.2. Some details of forehearth construction

The forehearth refractories are assembled in suitable steel framework, the whole assembly being usually suspended from 'I' beams above. This system makes it easy to allow the forehearth to expand during heat-up, and it can be levelled or provided with a gradient, if desired. It also has the advantage that it provides continuous free access to thermocouples as well as the burners and their supply lines and leaves room underneath for the multiplicity of equipment that has to be located for fibre forming. In the forehearth sections to which bushings will be attached, the base has

opening in steelwork and refractory for attaching the bushings. Each is mounted in a frame and is installed precisely by locating holes in the bushing frame onto pegs on the underside of the steelwork.

The internal width of a forehearth is governed by the volume of glass that has to flow through it at the temperature required for fibre forming. As an approximate guide a width of 400–420 mm for a 12–15 ton/day furnace with a 'T'-shaped forehearth would be normal; if the furnace was larger, e.g. 25 tons/day, and was provided with a 'T'-shaped forehearth, then the width of the upstream half of each section would have to be about 600–620 mm.

The depth of glass in the forehearth sections with bushings is critical for controlling the quantity of fibre made. It varies between 60–100 mm depending on the flow rate of glass through the forehearth required to feed glass to all bushings; indeed, at depths above 75 mm, the temperature of the glass itself near the floor of the forehearth is, in the main, a function of the flow rate of the glass and the temperature at which it entered the forehearth. If the flow is reduced while the level is high, one runs the risk of the glass at forehearth floor level becoming too cold, quite irrespective of the temperature maintained above glass level; this is due to the high infra-red absorption of the glass which is caused by its iron and chrome content. In extreme cases, glass at floor level or in the passages to the bushings can devitrify and lead to stones causing filament breakage during fibre forming.

The depth of glass in the refining and conditioning section of the forehearth is, at its upstream end, usually 75 mm greater than that in the bushing section. This depth is reduced within the conditioning section to that of the bushing section in one or two steps.

If a gradient is required to encourage glass flow towards the downstream end of forehearth sections, a slope of 1.5 mm/m length of forehearth is not uncommon.

Bushings are rectangular in shape (see Section 5.2). They can therefore be attached with their longitudinal dimension across or parallel to the length dimension of a forehearth. Figures 4.31 and 4.32 show the difference in internal construction of forehearths caused by these two methods. In both of these the heating is by burners firing horizontally. Figure 4.33 shows a cross-section of a forehearth where the firing is vertically downwards from a single row of burners.

A word about flues. The waste gas system of a forehearth should be completely separate from that of the melter. This means that the waste gases must be vented from the forehearth sections. Either a series of small openings are provided through the roof of the forehearth, in which the flue gases are vented from the section in which they are formed, or one or more flues are provided, in which case the direction of flow of the flue gases should be opposite to that of the glass flow, except in Section A (and Section D of fig. 4.28, if applicable). This means that a flue should be constructed at the meeting point of the three sections of a 'T'-shaped forehearth or over Section D of an 'H'-shaped forehearth. For very big forehearths, several flues would have to be provided. As to their construction, it should make it impossible for any condensate to drop back into the glass: this is best achieved by incorporating a right angle bend in the path of the flue as it leaves the forehearth.

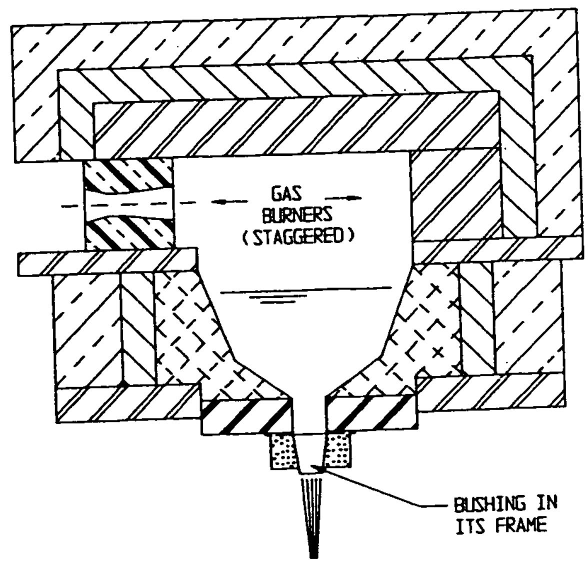

Fig. 4.31. Cross-section through forehearth with bushing attached, its length dimension parallel to the flow of glass. (Steelwork not shown; code of refractories given in fig. 4.4; inside width 200–400 mm, depending on glass flow required.)

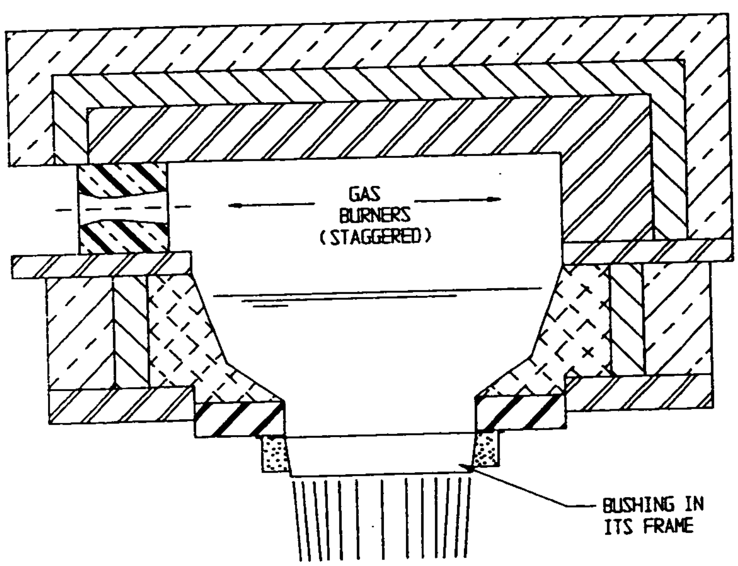

Fig. 4.32. Cross-section of forehearth with bushing attached, its length dimension at right angles to the direction of flow of the glass. (Steelwork not shown; for code of refractories, see fig. 4.4; inside width of forehearth 400–600 mm.)

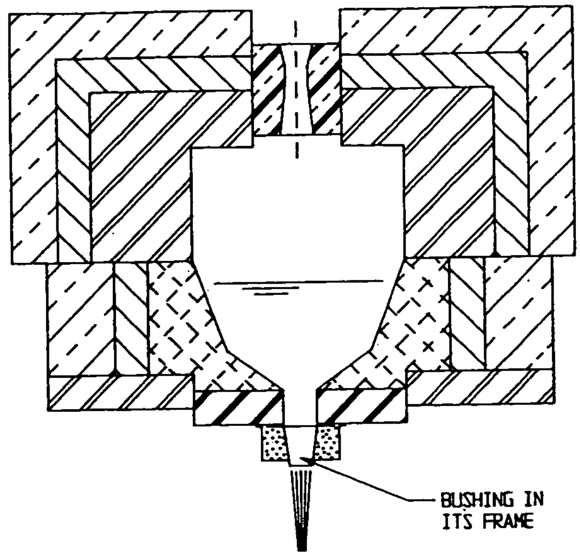

Fig. 4.33. Cross-section of forehearth with gas burners firing downwards from the roof.

The flue exit can lead via a cowl into a ventilator which conducts the waste gases to the outside of the building.

4.6.2.3. Choice of refractories

Refractories in the conditioning section (e.g. section A of fig. 4.27) have to withstand glass at a higher temperature than in the sections further downstream. The side walls here are dense chrome, backed by dense zircon or porous chrome. The glass contact refractories in the sections with bushings can be as shown in the fig. 4.31, 4.32 and 4.33. The glass contact refractory is porous chrome or dense zircon, which is backed and/or supported by high alumina mullite.

Mullite is used above the glass level. All forehearth sections must be well-insulated as energy consumption is considerable, about 30 000 kcal/h/m run of forehearth.

Some constructional details are worth noting:

(1) The corners between forehearth sections are subject to heavier wear and should therefore be made in dense chrome.
(2) The slotted blocks immediately above each bushing should be constructed of dense zircon and be in two longitudinal halves, the cuts being continuations of the slots through which the glass flows into each bushings. Porous chrome has also been evaluated in this position, but it is was found difficult to dislodge glass from its surface when bushings had to be replaced.
(3) With increasing size and flow of glass into bushings of high throughput, the

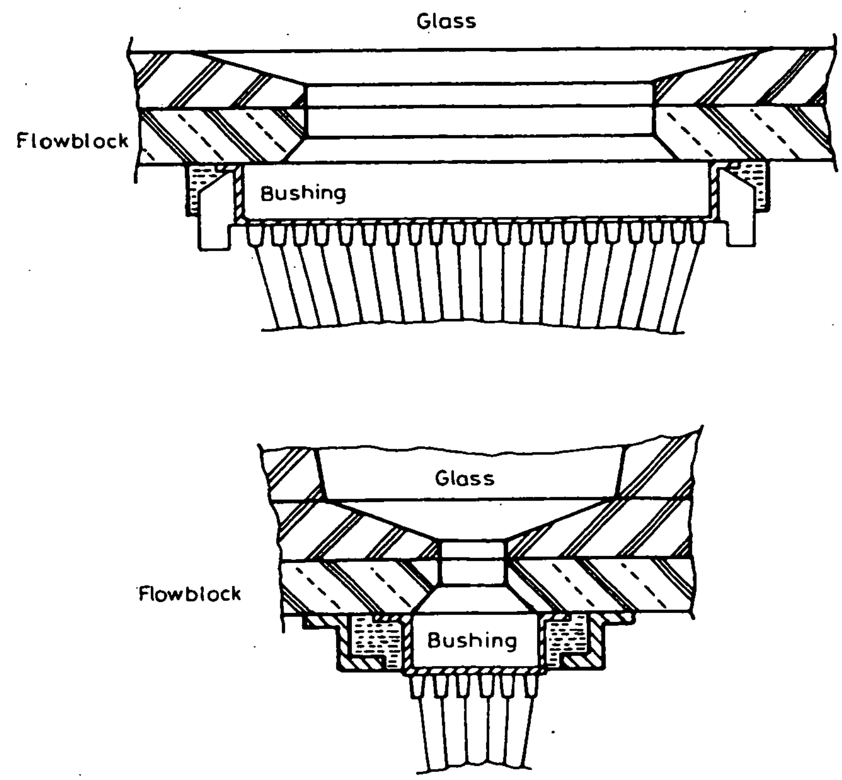

Fig. 4.34. As bushings become larger, the problem of maintaining a uniform temperature over the orifice plate becomes more difficult. The chamfering back of the underside of the flowblock above the bushing has been claimed to ease this problem.

design of the bushing flow block becomes more critical with respect to the ease with which the nozzle plate of a bushing can be maintained at a uniform temperature. The chamfering back of the bottom corners of the flow block (fig. 4.34) has been suggested as a way of solving this problem [32].

4.6.2.4. The firing system of a forehearth

The normal fuel is gas in one form or another: either coal gas, natural gas, butane or propane are used. The energy consumption is of the order of 25 000–32 000 kcal/h/m length of forehearth in the sections to which bushings are attached. In the refining/conditioning section the fuel consumption can be much lower due to the fact that here the glass is encouraged to cool.

Although the combustion air can be supplied from the main furnace air fans, the system is usually a completely separate one. In one well-tried system both gas

and air are fed into mixer/compressor which mixes air and gas in predetermined proportions and pumps the mixture under pressure to separate motorised pneumatic valves, one for each firing zone of the forehearth. From there the air/gas mixture passes to a manifold suspended above or near the forehearth which serves to distribute the mixture to the burners.

The main advantage of the premixed air/gas system is that it is usually operated in conjunction with a monitor and controller which tests the mixture prior to use and automatically adjusts the fuel/air ratio in order to control the excess oxygen content of the waste gases at a constant low level. The disadvantage is that the mixture is explosive and must therefore be operated with great care. The equipment must therefore be installed with flame traps and other safety devices to arrest any flame which begins to travel upstream in the supply lines; these safety devices are expensive and require regular checking and maintenance.

A simpler system is to use a system in which the mixing of air and gas takes place at the burner just prior to combustion. Each burner is preset by adjustment of a ratio adjustment screw in a small mixing chamber attached to the burner to give the desired mixture of gas and air. The supply of gas is governed by the air supply: if more fuel is required, the air flow increases and automatically calls for an increase in gas supply; accurate proportioning of air and gas is secured by the use of a zero gas governor. Since the gas is introduced only at the burner, the risk of explosion is virtually eliminated and the safety equipment reduced to a normal minimum for a gas system.

Depending on the width of the furnace, the number of burners per meter run of forehearth and the expected fuel input per burner, the individual burners are either placed opposite one another, in which case one manual valve governs the supply to each pair of opposing burners, or the burners are installed in a staggered configuration, in which case it is usual for a number of burners on each side to be controlled from one manual valve. Whatever happens, flame impingement on the wall opposite a burner must be avoided. An alternative burner system consists of radiant burners in the roof of the forehearth. All these systems are in use in the glass fibre industry.

The mounting of these burners has to be done remembering that movement will occur during the heat-up when the forehearth expands. This can be achieved by use of flexible pipes between supply lines and the burner. In addition, the burners should be sealed into their respective burner blocks to reduce noise and avoid burner nozzles becoming overheated.

The number of burners installed per metre run of forehearth varies from 8, if the forehearth is fired from above, to 2–5 on each side if firing is through the side walls. Burners can be either stainless steel pencil burners with a single hole as outlet, or ceramic disc burners in which the outlet is a disc with numerous holes providing a larger flame area with a larger number of small flames. Both types of burners, if used in a premixed gas/air system, have to be operated at a minimum pressure measured at the back of the burner, this minimum being governed by the need to prevent backward propagation of the flame into the pipe work. In this respect,

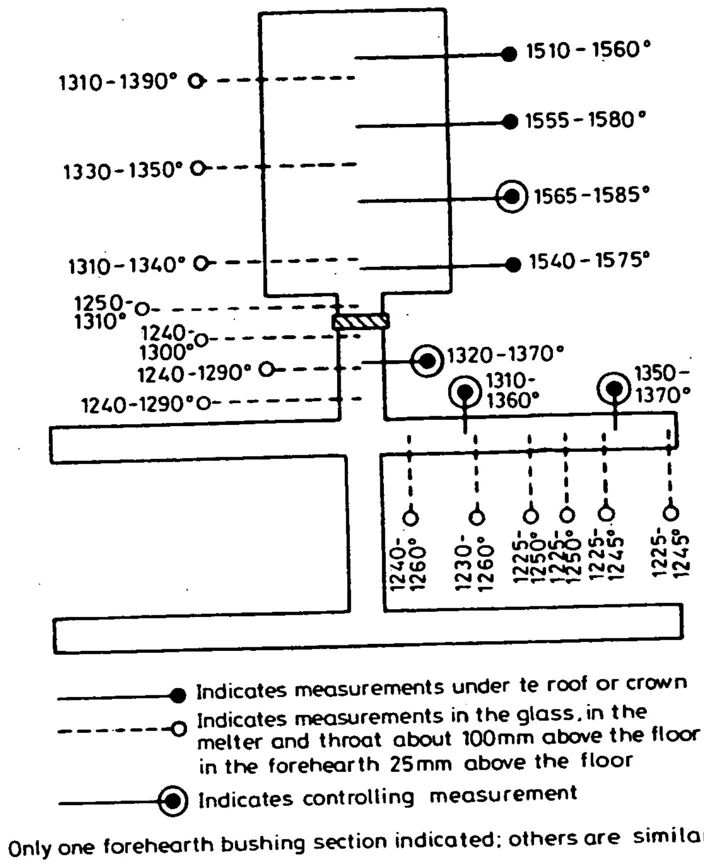

Fig. 4.35. Typical temperature measurements on a 10–20 tons/day direct-melt furnace and forehearth.

ceramic disc burners present a certain risk in that the ceramic disc can break, whereupon the new opening is insufficient to maintain the minimum back pressure at the burner; an explosion would result, although flame propagation backwards should be stopped at the flame trap.

Figure 4.35 is a diagram showing a typical temperature distribution for a unit melter and its forehearth. Each forehearth section is controlled for temperature separately. Although, for control purposes, one of the roof thermocouples (usually the centre one) is used because of its more rapid reaction to changing conditions, it is in fact the underglass thermocouple readings which govern its setting; it is the temperature of the glass which matters. If the depth of glass does not exceed

65 mm and once conditions are reasonably stable, it is possible to use one of the underglass thermocouples for control purposes.

The temperature of the glass from the time that it enters the forehearth to the moment that it flows into a bushing at the farthest bushing downstream should stay constant or fall slightly; up and down fluctuations should be avoided. The average temperature level in each zone is decided by the temperature of the glass itself, but is controlled by the control couple which acts on the motorised valve governing the fuel supply. The gradient within a zone is set by manual adjustments to the valves controlling pairs or groups of burners. These settings must be made under conditions which at least approximate to normal running conditions for glass flow, since the dynamic effect of the glass in terms of quantity and temperature makes its own energy contribution and therefore affects the thermal equilibrium.

It has been found that changes in the excess oxygen content of the forehearth flue gases have adverse effects on glass quality, especially if the excess oxygen content reduces towards zero. In areas where the composition of the gas varies – even if the calorific value does not – an automatic flue gas analyser, inserted between air/gas compressor and the distribution pipe work, can be linked to a controller which corrects for changes in the excess oxygen content by actuating a motorised valve to alter the proportions of gas and air entering the compressor. The excess oxygen content of forehearth flue gases are best kept between 0.5–0.8%.

All starters and controls of the forehearth firing system should be located in the furnace control room together with those for the melter.

4.6.2.5. Instrumentation, controls, alarms

Combustion must be safeguarded by connecting the gas/air compressor (and its stand-by) to the standby electricity generator (see Section 4.5.6).

Temperature control of each zone, as already mentioned, is carried out by selected thermocouples which act as controlling couples. Usually there are several extra couples both above and in the glass, perhaps 4 per zone which show variations within a zone and the gradient of glass temperature between entry and exit from a zone. These should be plotted in parallel on a recorder so that deviations are easily noted.

The glass level of both melter and forehearth is usually taken from a point a little downstream from the skimmer in the conditioning section of the forehearth. A variety of instruments are available in the glass industry; it does not matter which is used, provided the level is maintained to within 1 mm. Visual indicators made of stepped platinum alloy sheet are also often installed near the downstream ends of forehearth sections.

All recording instruments should be located in the furnace control room.

4.6.3. Electric heating of forehearths

The throughput of a bushing is directly proportional to the head of glass above the nozzles. In addition, the stability of the fibre forming process increases as the 'draw–

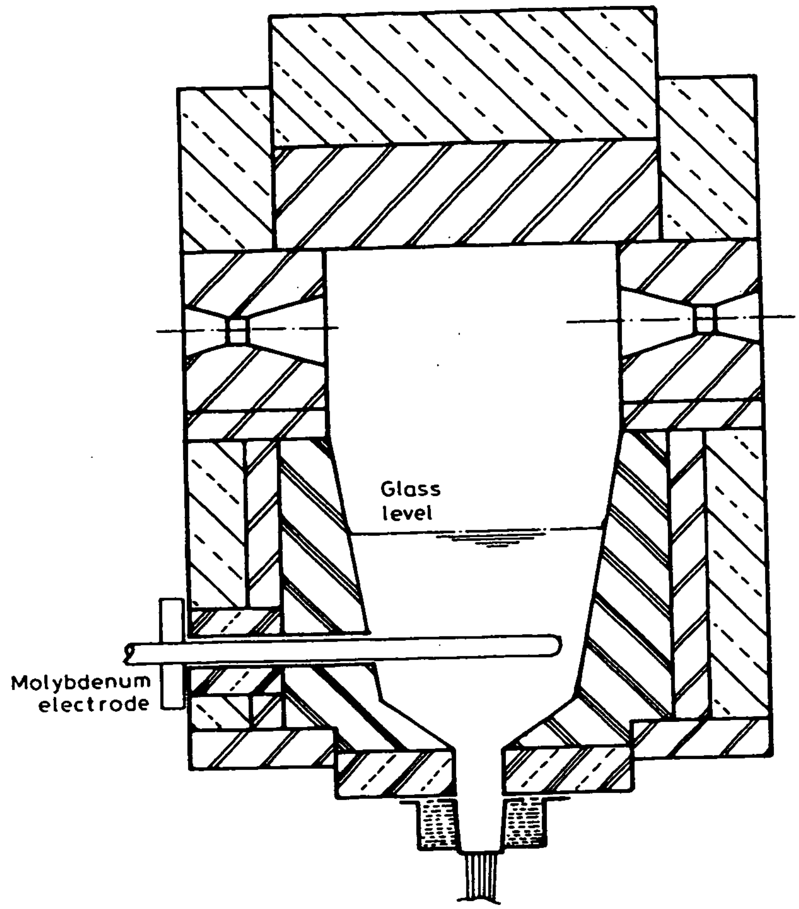

Fig. 4.36. Electrically-heated forehearth: the gas firing is only used during the heat-up and until glass to a depth sufficient to cover the electrodes is flowing in the forehearth.

down ratio', i.e. the ratio of nozzle bore to the diameter of the filament drawn from it, is reduced. It must therefore be an objective of the technology of fibre forming to increase the head of glass above the nozzles.

Since heating by gas flames above the glass cannot penetrate a depth of more than about 70–75 mm due to the high infra-red absorption caused by the presence of iron in E glass, the obvious solution lies in electrically heating the forehearth by means of electrodes inserted into the body of the glass.

This is established practice in the glass industry in general but has not spread to the glass fibre industry because of the high electrical resistance of E glass at the comparatively low temperatures prevailing in forehearths.

However, it has been tried, apparently with good results, but does not appear to have been taken up widely. The principle is straightforward: the forehearth is constructed as for gas firing, but holes are provided in the side walls so that molybdenum rod electrodes can be inserted horizontally through the side walls into the molten glass at distances of about 150 mm; one pair of electrodes are connected in turn to one phase of a three-phase power supply (fig. 4.36) [33].

The forehearth is heated up from room temperature using gas. When glass enters the forehearth, the electrodes are inserted. As these take over the heating of the glass, gas firing is stopped and the superstructure sealed and thermally insulated as far as possible.

This technique has enabled the glass height above bushing nozzles to be increased to 300 mm. Further increases in height may be achieved by lengthening the opening slot into the bushing, i.e. the flow block, by means of a vertical passage in which the glass is heated electrically via molybdenum electrodes [34]. The energy consumption of an electrically-heated forehearth is of the order of 6–8 kW/m length; This compares to an average consumption of about 32 000 kcal/h/m length of a gas-fired forehearth, which is equivalent to 37 kW/m length. This clearly demonstrates the improved efficiency of heating glass internally.

4.7. Technical control of glass manufacture

E glass contains two volatile constituents, fluoride and B_2O_3, both of which have a significant influence on glass viscosity and, therefore, ease of fibre formation. This applies equally whether the glass is used directly or is first made marbles for subsequent conversion into fibre by the remelt process.

It follows that the melting conditions of the glass should be kept as constant as possible. The problem is compounded by the fact that any difficulty which lengthens the time that the glass is in the furnace will yield a glass of lower B_2O_3 content and higher viscosity, thus increasing the difficulties of converting it into fibre and leading to further reduction in fibre production which, in the case of the direct-melt process, will further lengthen the dwell time of the glass in the furnace. In other words, the operation of a direct-melt furnace is in an unstable dynamic equilibrium.

It is therefore necessary to monitor all factors likely to influence the equilibrium, to use accumulated background data for establishing correlations, and from these to learn to recognise departures from normality quickly so that only small adjustments are needed to the control settings of the furnace in order to return the process to normal.

4.7.1. The commissioning of a unit melter and forehearth for the production of E glass

The commissioning of a glass furnace for the production of E glass, whether in the form of marbles or as liquid glass for feeding directly into bushings for fibre forming,

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5. The conversion of glass into glass fibre

This section deals with the fibre attenuation process using as starting materials either cold glass, e.g. in the form of marbles, or liquid hot glass supplied from a direct-melt furnace. The immediate products can be:

(1) Glass fibre strand wound into a fibre cake, i.e. one in which the inner diameter is cylindrical and the outside somewhat domed. A cake, after drying, is an intermediate product, unsaleable in this form, and therefore requires further processing. Examples of products which, at present, pass through the cake stage are chopped strand mats, rovings for chopping, chopped strands for reinforcing thermoplastics, and yarns.
(2) Directly-wound rovings in which the fibres have been wound into the shape of a roving directly during the attenuation process (see fig. 3.5). They only require drying before they can be packed for sale.
(3) Directly-chopped strands in which the fibre, immediately following attenuation, is passed to a chopping machine where it is cut to the required length(s), usually packed wet and is then used or sold for manufacture into tissue or roofing mat.

All the above fibre forming processes are the same as far as the fibre is concerned, namely that the liquid glass is attenuated mechanically at a speed which, taking into account the rate of flow of liquid glass from each nozzle, gives filaments of the required diameter.

When discussing the attenuation of glass into fibre and equipment required to carry it out, it is necessary to describe the attenuation process in general before dealing with the basic function of each piece of equipment in greater detail.

Figure 3.11 shows the equipment constituting a fibre forming unit in a diagrammatic form. It consists of:

(1) A bushing, or fibre forming furnace, which is a rectangular-shaped platinum-alloy furnace, with an opening at its top, and a multiplicity of nozzles – usually 200 or a multiple of 200, right up to 4000 or more – in its base. Most bushings are heated electrically. Located immediately under the bushing and very close to the nozzles are special cooling fins or pipes which stabilise the fibre forming process. In line with the base of the bushing, and usually adjacent to each long side of the bushing, are outlets for a supply of clean air into the fibre forming environment.
(2) Below the bushing and cooling fins or pipes are fine water sprays to cool the glass and to create an environment of high humidity.

(3) Next follows a fibre size applicator which provides a moving surface co with fibre size with which the moving fan of filaments makes contact, picking up the fibre size. The function of the fibre size is to provide lubrica and protection of the filaments and strand during processing and, in the of fibre destined for reinforcement, to deposit onto the glass surface spe chemicals designed to bond the glass fibres to the matrix material.

(4) Immediately below the fibre size applicator is a gathering shoe which col groups of individual filaments and combines them to form a strand or, for tain products, form a number of smaller strands, the strand in this case b referred to as 'split strand'. The gathering shoe can be stationary or it ca tate. In cases where the bushing provides two, three or four times the numb filaments wanted in each strand, the filaments can also be divided by provi a multiplicity of gathering shoes and winding each substrand separately i cake or roving.

(5) About 800 mm above the operator's floor level is the centre of the coll spindle onto which the fibre is wound to give a cake or a (direct-wound) ro In cases when directly chopped strands are made, the attenuation is prov by a pair of rubber-covered rollers through which the strand passes pri chopping. Each of these, whether the rotation of collet or spindle, or the ing of the strand through a pair of driven rubber-covered rollers, provid mechanical force solely responsible for the attenuation of the fibre.

Just before the strand(s) reach the collet of a winder or spindle of a r machine it becomes necessary to guide it so that, on deposition in a cake or ro it forms a package of the desired shape from which it is possible to unwin strand or roving smoothly without snarling or the formation of loops, etc.

In the case when cakes are being wound, the device used is a rotating wire tra designed to flick the fibre rapidly sideways in a zig-zag fashion, thus causin strand to be deposited at a small angle to the circumference; at the same the traverse reciprocates in and out, thus spreading the strands over the avai surface of the collet.

In the case of roving manufacture the guide is an eye reciprocating close t surface of the roving being wound.

It is important to realise that the fibre attenuation process is usually intermit fibre is wound continuously until a cake or roving of the required weight is obta the process is then interrupted in order that a new one can be wound. The w is limited by the need to remove the water of the fibre size picked up on pa over the applicator.

Manufacturers have been aware for a long time that, quite apart from the nomics of the operation, fibre forming itself operates at higher efficiencies i bushing is maintained under constant conditions of temperature and rate of flow. For this reason, small pull-down rollers are sometimes provided to enable to be drawn, albeit in a very coarse form, between the completion of one ca roving and the start of the next. This coarse fibre goes to waste. A better but

costly solution, as will be seen, is to invest in winding machines which automatically transfer the strand(s) from one collet or spindle to a second, thus continuing to produce saleable material with virtually no waste.

5.1. Marbles; quality control. Sorting and feeding of marbles to bushings

Marbles of E glass are usually made by companies which use them themselves for the production of fibre. This has several consequences. First, the price of marbles will be sufficiently high so that outside purchasers will not become serious competitors to the glass fibre producer who also uses marbles. Secondly, since the marble producer also uses them for his own production, he has the means to test each batch before selling them to outsiders; there is therefore no reason why marbles of poor quality should ever be sold except for uses when this aspect is not important, e.g. for melting down in a new unit melter during light-up.

The quality of marbles calls for consistency not only of composition and homogeneity but also of dimensions and freedom from surface dirt. Many batches of originally first grade marbles have been spoilt by poor packing causing marbles to pick up dirt on their surface. No amount of washing will ever return them to their original cleanliness; the washing may, indeed, make the problem worse.

Marbles should therefore be purchased against a purchasing specification of which the following, based on one issued by Nippon Electric Glass Co. Ltd. in Japan, is typical:

Type of glass:	E glass	
Diameter of marble:	21.5 mm ±1.0 mm	
Cleanliness of marbles:	Clean, free of dirt, broken glass and contamination.	
Freedom from strain:	Marbles will not break during feeding nor shatter during melting.	
Packing:	Five-ply paper bags each containing 50 kg, or wooden case lined with polythene sheet each containing 1500 kg.	
Composition:	SiO_2	54.8% by weight
	Al_2O_3	13.6
	B_2O_3	7.9
	CaO	22.2
	MgO	0.6
	$BaO+SrO$	0.3
	Fe_2O_3	0.2
	R_2O	0.4
Refractive index:	1.562	

Density:	2.61
Coefficient of thermal expansion (30–380°C):	$56 \times 10^{-7}/°C$
Annealing point:	680°C
Softening point:	847°C
Temperature at which viscosity is 10^3 poise:	1200°C
Frequency of primary filament breaks: when operating a bushing of ... nozzles making filaments of ... micrometers diameter:	to be agreed

Consistency of composition is assured to some degree by consistency of the so ening point, although the throughput of a given bushing is a more reliable and mc meaningful parameter. Refractive index and density are very sensitive to changes composition; in addition, the refractive index is also important in connection wi the manufacture of transparent polyester-glass composites, when the refractive dices of glass fibre and polyester have to match. As for dimensions, the numb of marbles per kg or per lb is a good indication of the average diameter; the ameter itself is important for consistency of feeding the marbles down pipes ir bushings. Excessive strain can cause marbles to fracture explosively when enteri the bushing, or it can cause breakage in and blockage of feed pipes. Lastly, gl marbles can only be judged in relation to their performance when drawing fibr this should be decided in relation to the number of primary fibre breaks per ho secondary breaks are those caused by the primary breaks and should be ignored the purpose of this test.

Marbles should be supplied to the specification and should not need sorting.

Marbles available in the open market are about 20 mm in diameter. Some co panies make marbles of 25 mm diameter for their own use.

The feeding of marbles into bushings is intrinsically simple. In principle, marbles are allowed to roll out of a hopper into a trough where they form a sin layer. This trough is vibrated or gently tilted forwards and backwards to roll marbles so that they can fall through one or more holes in the trough, each which is linked to a set of feed pipes each leading directly to one feed hole of bushing. The feed pipes can be of coiled wire, or they can be of iron; whiche it is, the pipes of the last 50 mm or so just above the bushing should be stainl steel for reasons of temperature. This stainless steel pipe should end about 5 r above the feed hole entrance of the bushing itself where it must be located rigi and centrally.

Feed pipes should always be full of marbles as a change in the weight of marb in a pipe is equivalent to a change of head of glass in the bushing; also, if marb

have jammed and are then released by operator intervention the impact of a rush of marbles down a pipe acts as a kind of hammer blow on the bushing itself – a thing to be avoided. To avoid this risk, warning systems using photoelectric cells can be fitted to the supply lines; in addition, some manufacturers locate low-power vibrators onto the feed pipes to keep the marbles on the move.

5.2. The fibre drawing furnace – the bushing

Glass fibres are produced by the rapid attenuation of drops of molten glass exuding through nozzles under gravity and suspended from them. The dynamic balance between the forces of surface tension and mechanical attenuation results in the drop of glass taking on the shape of a meniscus held on the annulus which constitutes the outlet of the nozzle and tapering to the diameter of the fibre being drawn. For fibre drawing to be successful the glass has to be within a narrow range of viscosities, i.e. between 600 and 1000 poises. At lower viscosities the glass is too fluid and falls away from the nozzles as drops: in this case surface tension dominates. At higher viscosities the tension in the fibre during attenuation is too high; furthermore, the rate at which glass flows through a nozzle can become too low to maintain a stable meniscus. There must be a balance between the volume of glass being formed into fibre and the rate at which the meniscus is being replenished from the nozzle to maintain it.

The rate at which fibre is produced from a given nozzle is entirely a function of the rate of flow of glass through this nozzle and is independent of the rate of attenuation, i.e. the diameter of the fibre being made. If the rate of attenuation is decreased the fibre will simply assume a larger diameter and vice versa.

The rate of flow of molten glass through a nozzle can be described in relation to Poiseuille's equation as:

$$F \propto \frac{r^4 h}{l\eta},$$

where F is the rate of flow in g/h, r is the radius of the nozzle in its narrowest cylindrical section, l is the length of this cylindrical section, h is the height of glass above the nozzle, and η is the viscosity of the glass (see fig. 5.1). During fibre forming, cooling causes the viscosity of the glass to increase in the course of its passage down the nozzle; it is, therefore, not possible to predict exactly the flow rates from nozzles of different designs, since the rates of cooling and, therefore, the increases in viscosity may differ also. However, for a nozzle of given design the Poiseuille relationship can be used to alter the dimensions of the nozzle to effect a specific change in flow rate, especially when considering direct-melt bushings supplied with liquid glass. With bushings fed by marbles, the situation is more complex as the body of semi-molten glass of high viscosity positioned above the liquid glass can change as the flow rate through nozzles is increased, and exert a kind of drag effect on the glass flowing out of the nozzles. In this case some

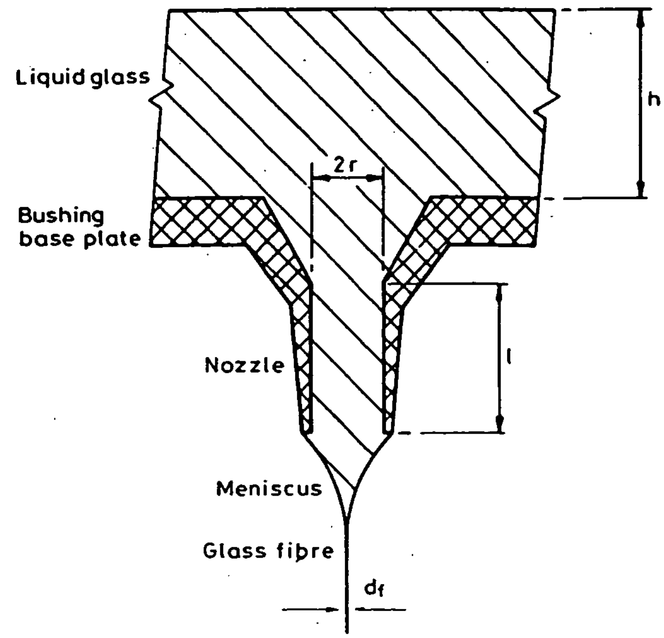


Fig. 5.1. A nozzle in an orifice plate of a bushing showing the meniscus formed during att of the glass into a fibre.

manufacturers have found that $F \propto r^{2.5}$ more accurately reflects the relat between flow rate and nozzle diameter.

The function of a bushing is to provide a plate containing a multiplicity of at uniform temperature and to condition the glass to this uniform tempera that the fibres drawn are of uniform diameter. Bushings are of two kinds: th type is the 'remelt bushing' (fig. 5.2) using marbles or glass of other shapes a material. It serves two functions, first, to melt the cold glass in its upper secti second, to condition this glass and pass it through nozzles for attenuation. bushings are still in widespread use for the manufacture of fine fibres o diameter or under, or for speciality products when the requirement is inter or of small volume.

The newer type, now approaching its 50th anniversary, is the direct-melt b (fig. 5.3), which is supplied with liquid glass at about the correct temperat fibre forming from a continuous supply flowing above the bushing in a channe the forehearth. In this case the bushing has to provide only the second fu namely to condition the glass to the best temperature for fibre forming. Due fact that a direct-melt bushing only has a single function, it is much shall

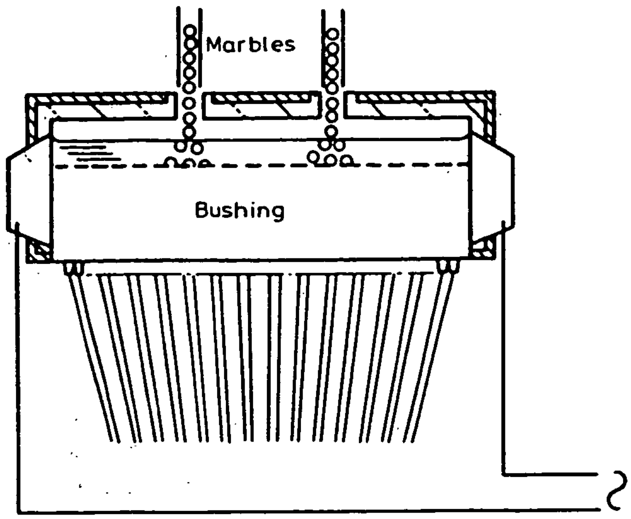


Fig. 5.2. Schematic of a remelt bushing. The broken line within the bushing is a heated perforated plate which retains the unmelted marbles.

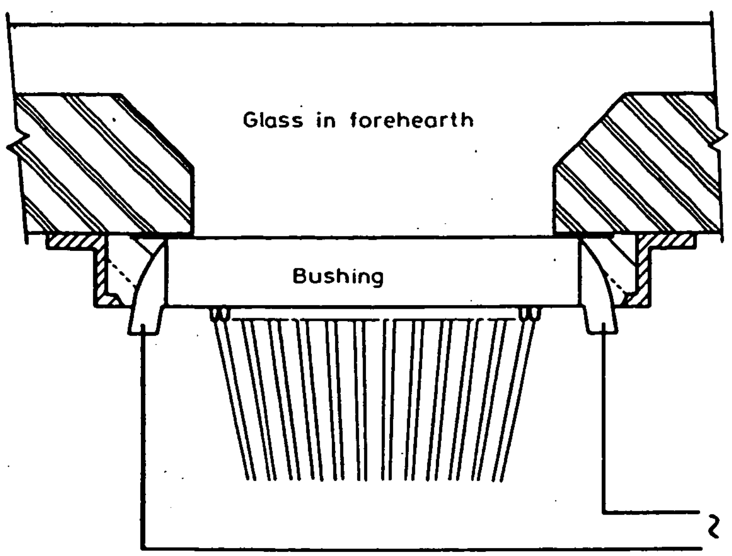


Fig. 5.3. Schematic of a direct-melt bushing attached to the underside of a forehearth from which liquid glass is supplied.

construction: broadly speaking, a remelt bushing with a given number of nozzles will weigh twice as much as a direct-melt bushing with the same number of nozzles.

The design of bushings is largely empirical. For reasons of resistance to attack by molten glass and stability at the temperatures needed for fibre forming, bushings are made from platinum group metals, usually platinum–rhodium alloys. The proportions are varied, together with the design to some extent, depending on the cost of these metals; with the cost of rhodium a multiple of that of platinum, its use is restricted to the essential, i.e. to increase the stiffness of the material. If it is assumed that the average platinum–rhodium alloy used in a glass fibre plant is 13%Rh·87%Pt, that the annual production from one bushing yields between 50 and 500 tons of products per year, and that bushings weigh between 1.5 and 7.5 kg each at a current value (July 1992) of US$ 33.2/g of alloy, then it is clear that a substantial part of the investment in a glass fibre plant is in platinum group metals. And this is not all: significant amounts of these metals are used also in the melter and forehearth for lining of the skimmer, bubblers, and thermocouples and their sheaths. Fortunately, only a little is lost in use, and between 97 and 99% of the original weight can be recovered when bushings and other platinum metal components are scrapped and the metal is recovered. Repeated attempts to find alternative materials from which bushings can be constructed have all failed as they are expensive to make and give only a very short life, thus increasing the cost of manufacture of fibre while lowering the quality of the product at the same time.

However, the search for alternative materials is by no means a dead issue: more recently, work has been done aimed at developing bushings made from platinum-clad stainless steel with nozzles made from platinum metal tubes, inserted into punched holes in the orifice plate and consolidated there by isostatic pressing [1].

For the present, the use of platinum metals appears unavoidable. There is, however, considerable economic pressure to reduce the amount of platinum metal employed per unit weight of fibre produced; one way is to raise the output of a bushing to a maximum; the other is to replace existing designs of bushings by others which require less platinum metal per unit of output. The latter is being achieved with larger bushings of high throughput. These will be discussed later (see Section 5.2.4 below).

The bushings themselves, with the exception of the nozzle plate and the entry holes for glass or marbles are encased in (thermal) insulating refractory held in a metal frame. When in use, direct-melt bushings are attached to the underside of a forehearth; remelt bushings are individually suspended from a suitable steel framework linked to the marble feed system.

5.2.1. The choice of platinum metals and the alloys used

Platinum metals are used because of they are virtually insoluble in the glass that they hold; this means that the metal is resistant to corrosion by the glass and therefore does not contaminate the glass. The bore and other dimensions of the nozzles remain constant, thus ensuring that one of the factors governing the diameter of

fibre produced is not variable. It also follows that the bushing does not change its electrical cross-section and that its electrical resistance and the pattern of temperature distribution created when the bushing is connected to the electrical supply for heating remains fixed.

Furthermore, platinum metals at the temperatures at which they are used are resistant to oxidation: in this respect they are unique. Theoretically at least, molybdenum and tungsten would make good materials for bushings if it were not for their very poor resistance to oxidation.

However, with age the metal takes on a decidedly crystalline appearance, a phenomenon referred to as 'thermal etching'. It is caused by the preferential evaporation of rhodium at grain boundaries from where it spreads and is the cause of weakening of the metal with age.

A factor in the selection of platinum metal alloys, etc. is resistance to creep at elevated temperatures. Creep is really deformation under load and is a function of stress. For a given alloy or metal, the rate of creep increases with increasing temperature. Since a bushing is expected to have a useful operating life and since creep and distortion is often the factor limiting the useful life of a bushing, this is clearly an important property.

A further factor is the contact angle between liquid E glass and platinum alloy at the operating temperature of the bushing. This is important for all designs of bushing whether with nozzles or just with holes (see Section 5.2.5), since it governs the cleanliness of the orifice plate and can lead to crystals of devitrified glass becoming entrained in the fibres and weakening them, thus running the risk of filament breakage during production.

Pure platinum is rather soft and distorts quickly at normal operating temperatures. The addition of rhodium strengthens and stiffens the metal and reduces the rate of creep; however, it makes the working of the metal and fabrication into bushings more difficult, a problem that has been overcome with experience. Pure platinum has a rather low contact angle with liquid E glass at fibre forming temperatures. This gives rise to the problem of glass wetting the outside of each nozzle and creeping up on the outside towards the bottom of the orifice plate. Initially, this problem was controlled by design, namely by providing the nozzle with a counterbore; this provided a smaller annulus from which the meniscus was suspended and prevented glass from creeping up the outside of the nozzle. A small annulus also brought the benefit of drops of glass, formed when there had been a filament breakage, falling away more quickly thus permitting a more rapid restarting of the fibre forming operation. The introduction of rhodium, initially as 10%Rh-Pt, raised the contact angle and gradually made the counterbore unnecessary, thereby eliminating an expensive drilling operation.

The problem of metal–glass contact angle has also been attacked by adding gold to the alloy [2]. Unfortunately this softens the alloy or, when used only in selected parts of a bushing, e.g. the nozzles, the gold migrates at operating temperatures into adjoining platinum metal parts thus weakening them: at the same time, the

beneficial effect of the gold addition, at the position where it was supposed to be, i.e. the nozzles, is lost.

As bushings increased in size, the problem of creep began to dominate. This was tackled by supporting the orifice plate externally (see fig. 5.15) and/or using 20% rhodium–platinum alloy. When expressed in terms of cost per volume of metal, the price of this alloy was initially not significantly different to that of platinum. With the large demand of rhodium for catalytic converters of motor vehicles this is no longer the case and, in July 1992, the price of rhodium is over eight times that of platinum in terms of weight, and five times in terms of volume. Also, the operating losses of rhodium are greater than those of platinum due to very slow oxidation of rhodium in air and the evaporation of this oxide from exposed surfaces of the metal. Areas of metal not exposed, i.e. those encased in refractory, also suffer losses and weaken, but the oxide dissociates as it cools and most of the metal lost in this direction condenses in the interior of the refractory from which it can be recovered.

The problem of creep has also been attacked by a different route, namely by the introduction of dispersion-strengthened platinum and platinum–rhodium alloy [3]. The addition of a highly dispersed phase of specific oxides, of which zirconia, yttria, and thoria are examples, and in quantities as low as 600–1000 ppm gives platinum or platinum–rhodium sheet a stable fine fibreous microstructure compared to a crystalline structure of the oxide-free metal sheet [4]. This fibrous structure is of considerable benefit in reducing the deleterious effects of temperature on mechanical properties at the elevated temperatures employed.

The fine fibreous structure of dispersion-strengthened platinum metals is destroyed on melting. There is therefore a problem when parts are joined by welding. Voids may also occur due to preferential diffusion effects across the joint, and leakage may result. The problem can be overcome by design; for example, welds are moved to areas where the advantageous properties of the dispersion-strengthened material are not required or are not important.

Dispersion-strengthened platinum and its alloys, when used for selected parts of a bushing, should only be joined to non-dispersion strengthened parts made of the same alloy. If they are different alloys, porosity will result along the welds due to high-temperature interdiffusion [5].

The advantages of dispersion-strengthened platinum metals are not only the reduction of creep and increase in strength but also

- possibly, a reduction in the rate of oxidation of rhodium in air which would imply a reduction in metal losses due to this cause;
- a greater tolerance to attack by deleterious metals, e.g. silver, a matter of some importance for plants using nozzle coolers (see Section 5.2.6) in the form of silver fins [6];
- a reduction in work hardening when compared to high rhodium–platinum alloys, making manufacture of components easier; and
- possibly, an increase in the contact angle between glass and metal which may be due to the fine crystalline structure of the dispersion-strengthened metal rather

than the presence of dispersed oxides (which are, after all, slightly soluble in the glass).

The advantages of the use of dispersion-strengthened platinum metals are still subject to debate as the increase in bushing life has not always been realised. Obviously, if failure was due to causes other than creep, a comparison is not valid. However, in instances when creep was believed to have been the reason for failure, the distortion of the original plate was often caused by insufficient allowance being made for thermal expansion when heated to the operating temperature. Even when correct allowances are made compressive stresses can be set up between refractory used for encasing the bushing and the bushing itself due to differing dilation rates: the bushing dilates more quickly than the refractory which requires more time 'to catch up'. Under these conditions distortion can take place resulting from the very high compressive stresses being set up.

In theory, there is no reason why strength and creep properties of platinum metals at elevated temperatures should not be further improved by raising the quantity of dispersant in the metal. This is limited for the present by problems in the manufacture of ingots and sheets of sufficient size to have uniform repeatable properties and be industrially useful.

The use of platinum metals having lower creep rates and higher strengths at elevated temperatures is clearly important for orifice plates of large bushings where it should significantly extend bushing life. In addition, it should also find use in platinum metal components used in the melter and forehearth where such components are liable to bend or sag: bubbler tubes and thermocouple sheaths inserted upwards through the floor are examples.

The problem of creep at elevated temperatures can also be attacked by design without resorting to the use of dispersion-strengthened platinum metals. The orifice plate can be thickened, supporting beams can be welded on the inside of the orifice plate at regular intervals, or beams can be welded into the side walls higher up in the bushing and wires suspended from them which are welded into the orifice plate. One solution attempted (see Section 5.2.5) was to eliminate nozzles as such and operate using holes instead, this enabling the size of orifice plates to be reduced very significantly for a bushing of given numbers of filaments and stated throughput. The overriding problem then became that of glass wetting the orifice plate whenever filament breakage occurred. The use of gold–platinum alloys was tried but did not provide an adequate answer to the problem. Although a few bushings of this type are still in operation, they are clearly falling out of use.

Care has to be exercised is the handling of platinum metals and the use to which they are put. Elements such as arsenic, antimony, bismuth, tin and lead are 'poisons' to platinum metals as they have a critical effect on the high-temperature strength of platinum metals. The quantities permitted to be present in platinum metals for use are therefore limited to 10 parts per million each with the combined total of any four being limited to 30 parts per million. In addition, organic materials (which can accidentally fall into remelt bushings) cause instant failure due the platinum

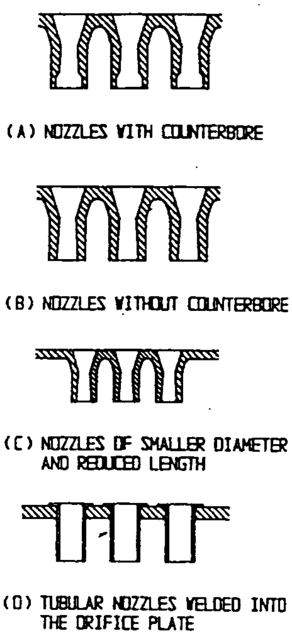


Fig. 5.4. Examples of nozzle shapes giving similar throughputs of glass. It is clear that no (C) can be placed closer together thus saving platinum alloy or allowing more nozzles per u of orifice plate. The tubular nozzles in (D), because of their thin wall, allow more rapid of the glass, thus allowing the glass in the bushing to be hotter and increasing the throug glass.

surface acting as a catalyst to effect the reduction by carbon of some glass to the metal, e.g. SiO_2 to metallic Si; this immediately alloys with platinum ı to form a low melting point alloy which leads, without fail, to the formatio hole in the bushing.

5.2.2. The nozzles

The rate of fibre production is independent of the rate of attenuation an function only of the rate of flow of glass through the nozzles. There are, ho some practical limits to the rate of attenuation and the flow rate of glass th a nozzle on its way to attenuation.

(1) A practical limit to the amount of glass which can flow through a no: a bushing appears to be about 45 g/h. There is no theoretical basis fc figure – it is based on experience and may be connected with the amo cooling to which the glass can be subjected on its way through a nozzle.

(2) It has been shown that the stability of the meniscus, i.e. that part of the meniscus on which molten glass is rapidly thinned down to the final fibre diameter (fig. 5.1), decreases as rates of attenuation increase above 2500 m/min. [7]; in other words, for reasons not fully understood, but probably connected with the increasing volume of air being sucked into the fan of fibres as they are being drawn (see below), the frequency of fibres breaking at the meniscus increases as the attenuation rate climbs above this figure. Fortunately, the rate of fibre breaks does not increase all that rapidly. Most manufacturers draw fibres , especially fibres finer than 10 μm at higher rates and let economics decide the optimum while also investing effort designed to remove the causes of filament breakage. Attenuation rates in the region of 3000–4000 m/min. are not uncommon for fine fibres. However, for bushings with very large numbers of nozzles, e.g. of 800 nozzles or over, it has been found best to reduce the attenuation rate to minimise the frequency of filament breakage [8]. Reference has already been made to the influence of the air which is being drawn into the fan of fibres and which is projected downwards with the fibres. The fan of fibres acts as a kind of suction pump. If this air is not clean, or if the flow is turbulent, then filament breakage could well result [9].

(3) The stability of the meniscus is in part a function of the drawdown ratio, i.e. $2r/d_f$ (see fig. 5.1). It is better to have a small bore and shorter cylindrical section than a larger bore with a long cylindrical section. Hence also the importance of the head of glass over the nozzle: if it could be increased, then more fibre could be produced without adversely affecting the stability of the meniscus.

(4) With increasing attenuation rates, the condition of all surfaces over which the fibres are being drawn on their way from the bushing to the collet of the winder (or other means of attenuation) (see e.g. fig. 3.11) becomes progressively more critical. These are the surfaces of the applicator, guide(s) and traverse.

(5) The shear forces created by fibres passing at high speed through the film of fibre size on the belt or roller of the applicator can break down the fibre size (which is often a suspension). This can lead to coagulation of certain components which are deposited as solid particles in the path of the fibres; these will cause fibres to break and the fibre forming process to be interrupted.

For every type of fibre there is, therefore, an economically optimum attenuation rate which should be the governing factor in the design of the nozzles. It is, of course, always possible to make coarser fibre by reducing the attenuation rate, but, while not impossible, it is impractical and uneconomic to manufacture finer fibres by simply increasing the attenuation to above that for which the bushing and the nozzles were designed. The highest attenuation rates reported appear to be about 5000 m/min.

To a large extent, the design of nozzles, as currently used, arose out of the development of materials and techniques. Originally, bushings were made from pure platinum, a metal which is easily wetted by molten glass. This causes the glass

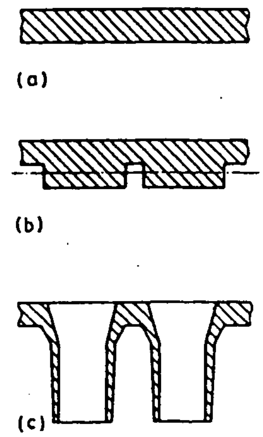


Fig. 5.5. Schematic of the manufacture of a bushing orifice plate by coining and deep

to run up the outside of the nozzle, spread over the underside of the ori: from which the glass would then have to be removed by a very tedious operation before fibre forming could be restarted. It was found that this could be eliminated by providing the nozzles with a counterbore (fig. 5.4(a platinum–rhodium alloys, which are not so easily wetted by molten glass, troduced, the counterbores remained. It was some time before it was reali even for pure platinum, not the counterbore, but the thickness of the nozz its open end, was the important aspect. The explanation is straightforwa glass first flows through the nozzle, it forms a drop suspended from the ring which constitutes its outlet, then falls away when the weight of gla drop exceeds the value that can adhere to this annular ring. The weigl drop is a function of the area of the annular ring. Therefore the thinner tl the nozzle exit – counterbore or no counterbore – the faster will a drop f away and leave a fibre attached to the meniscus suspended there, and th the tendency for glass to remain there and gradually climb up the outsi nozzle. The time taken for a drop to form and fall away is an important the time lost whenever a filament breaks during fibre forming and the pr to be restarted.

Figure 5.4 shows four examples of nozzle shapes. In recent years there h moves to reduce the size of the orifice plate by making the nozzles shoı (c) which means that, for a given throughput, they can be placed closer (d) is a more recent development in which pre-manufactured nozzles m platinum alloy tubes are inserted into holes drilled/punched into the ori: and are then secured by welding from the inside, preferably by laser weld

Most nozzle dimensions of lie within the following ranges:

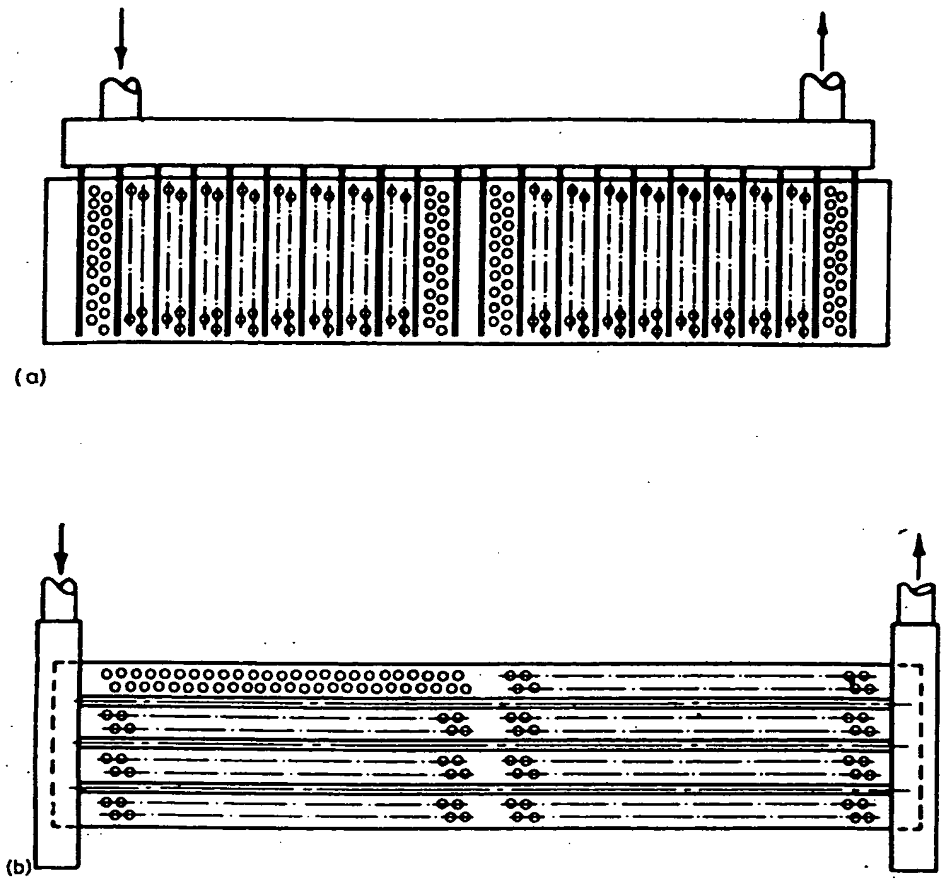


Fig. 5.6. The layout of a bushing orifice plate is governed by the type of nozzle shield employed. In these examples there are shields between alternate rows of nozzles; in some, more critical cases, shields are placed between every row.

Overall length below the orifice plate	3–6 mm
Length of cylindrical section	2–6 mm
Bore of cylindrical section	1–2.5 mm

While the overall length of nozzles is partly a function of tradition, it is also related to the need to provide time for cooling the glass and, in most cases to provide distance for the location of nozzle shields (see fig. 5.6 and Section 5.2.6). The combination of diameter and length of cylindrical section is chosen to give the desired flow of liquid glass bearing in mind the effective head of glass above the nozzles and the need to bring the glass temperature to a value suitable for fibre forming, i.e. to a viscosity of about 10^3 poise.

Table 5.1 gives modified Poiseuille's equations related to different designs zles or orifices of bushings.

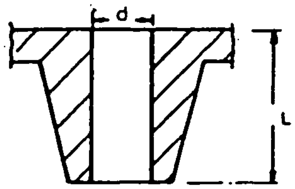
The techniques for making orifice plates containing a multiplicity of noz: four, all of which are in use. The oldest method is to take as sheet of pl metal, usually 1 mm thick, mark on it the centre position of each nozzle, t means of a simple tool, place a small indentation into the sheet at each position. This is followed by melting platinum or platinum alloy wire in an o hydrogen flame and allowing drops of the metal to be deposited onto the ap each indent. Periodically, the accumulated metal at each nozzle position is in a press tool which confirms or slightly enlarges the indentation on the inl of the nozzle while it shapes the outside to the contours of the nozzle, i.e. th truncated cone. When sufficient platinum metal has been deposited and the shaped, the overall length of the nozzles is made uniform by machining th of the nozzles to a uniform height. This is followed by drilling out the bor a centering tool. The counterbore, if required, is subsequently drilled out machine with set limited travel. It is important that all drilling is done with tools as rough surfaces cause reductions in the flow rate of the glass throu nozzle. Although this method is very tedious and time consuming, it is still and gives good results.

The second method consists of punching a hole in the sheet at each noz: sition, followed by inserting pre-manufactured solid nozzles and welding the the sheet. Drilling and counterboring, if used, follow as above. This metho very good uniformly-shaped nozzles.

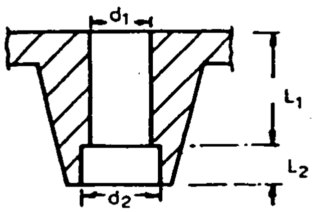
The third method was developed in the 1960's and made use of known drawing techniques used with other metals and for other purposes. Instead of ing with a sheet of platinum metal of the final thickness, e.g. 1 mm, the s of such a thickness that it contains all the metal of the sheet at its final thi plus the metal for the nozzles, the metal which constitutes the hemispheres ing the outlet of each nozzle and any other operating waste. Figure 5.5 sho manufacturing stages of this process. In stage 1 the sheet is progressively st to provide coin-like protrusions wherever a nozzle is to be located and the c final thickness of the metal between these protrusions. The diameter of each is the diameter at the base of each nozzle. After annealing, the nozzles are drawn from these 'coins' in two or three draws, with annealing between each if necessary. This provides an orifice plate of high quality with uniformly-s nozzles possessing smooth bores. Originally they had to be provided with a taper of about 3° for successful deep drawing; this is no longer necessary. Tl a limitation on the dimensions of nozzles which can be made this way: the r length of cylindrical bore (plus counterbore, if any) to the bore itself shoul reasons of cost, not exceed 2.0.

The fourth method is derived from the second. Instead of using premanufa nozzles for insertion into the holes punched in an orifice plate, lengths of pla metal tube of uniform wall thickness are inserted and secured by welding, p ably by laser welding. This provides nozzles of very uniform dimensions an

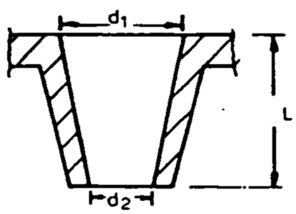
Table 5.1
Modified Poiseuille's equation for various shapes of nozzles, assuming constant η and h.



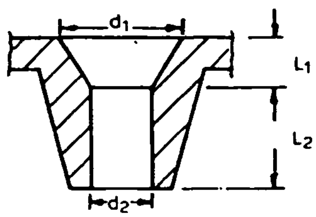
$$F_1 = K_1 \frac{d^4}{L}$$



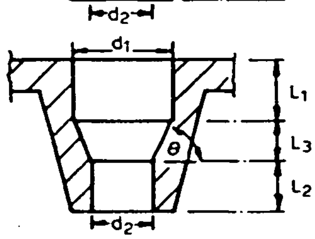
$$F_2 = K_2 \frac{1}{\dfrac{L_1}{d_1^4} + \dfrac{L_2}{d_2^4}}$$



$$F_3 = K_3 \frac{3d_1^3\, d_2^3}{L\,(d_1^2 + d_1 d_2 + d_2^2)}$$

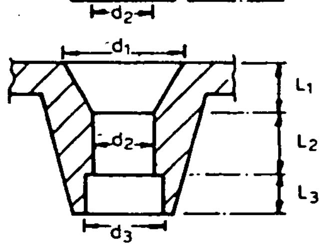


$$F_4 = K_4 \frac{1}{\dfrac{L_2}{d_2^4} + \dfrac{L_1(d_1^2 + d_1 d_2 + d_2^2)}{3d_1^3\, d_2^3}}$$



$$F_5 = K_5 \frac{1}{\dfrac{L_1}{d_1^4} + \dfrac{L_2}{d_2^4} + \dfrac{L_3(d_1^2 + d_1 d_2 + d_2^2)}{3d_1^3\, d_2^3}}$$

$$\text{or } K_5 \frac{1}{\dfrac{L_1}{d_1^4} + \dfrac{L_2}{d_2^4} + \dfrac{\tan\theta\,(d_1^3 + d_2^3)}{6d_1^3\, d_2^3}}$$



$$F_6 = K_6 \frac{1}{\dfrac{L_1\,(d_1^2 + d_1 d_2 + d_2^2)}{3d_1^3\, d_2^3} + \dfrac{L_2}{d_2^4} + \dfrac{L_3}{d_3^4}}$$

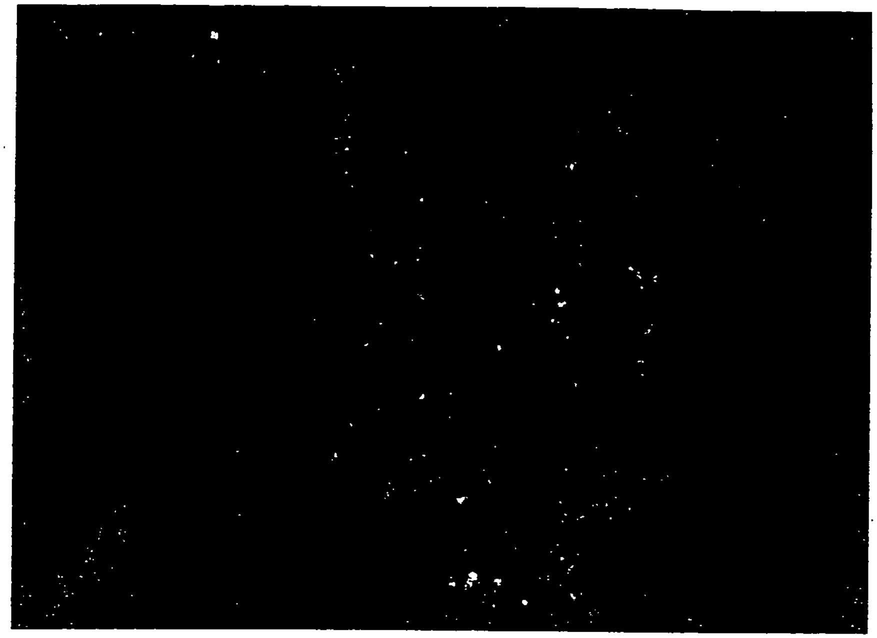


Fig. 5.7.a. Glass fibres of non-circular cross-sections: bilobal (a) and trilobal (b) glass fibres signed to provide more contact area per unit weight between glass fibres and polymer. (Cour of Owens-Corning Fiberglas Corporation.)

thickness which is usually 0.2–0.5 mm. The fact that the wall thickness is unifor low all the way up into the orifice plate leads to more rapid cooling of the glass it leaves the bushing, a fact which enables higher throughput rates to be achiev

For reasons of economy it is desirable to place nozzles as closely together possible. The minimum distance is, in part, governed by manufacturing te niques as space must be provided between nozzles, for example, for welding pre-manufactured nozzles, or for tools used in deep-drawing. Centre-to-centre c tances of between 4 and 5 mm are usual. Space can be saved in pairs of rc by staggering; the distance between adjacent nozzles remains the same, but t distance between rows becomes $\frac{1}{2}\sqrt{3}$ of the distance between nozzles in a row.

The remaining layout of all nozzles of a bushing in its orifice plate is goverr by the type and design of nozzle shields which are used. These will be discussed some detail later (see Section 5.2.6). At this stage it is sufficient to state that tl are basically of two types, the transverse (fig. 5.6(a)), in which the nozzle shie are positioned across the width of the bushing, and the longitudinal (fig. 5.6(b)) which they run parallel to the length of the bushing.

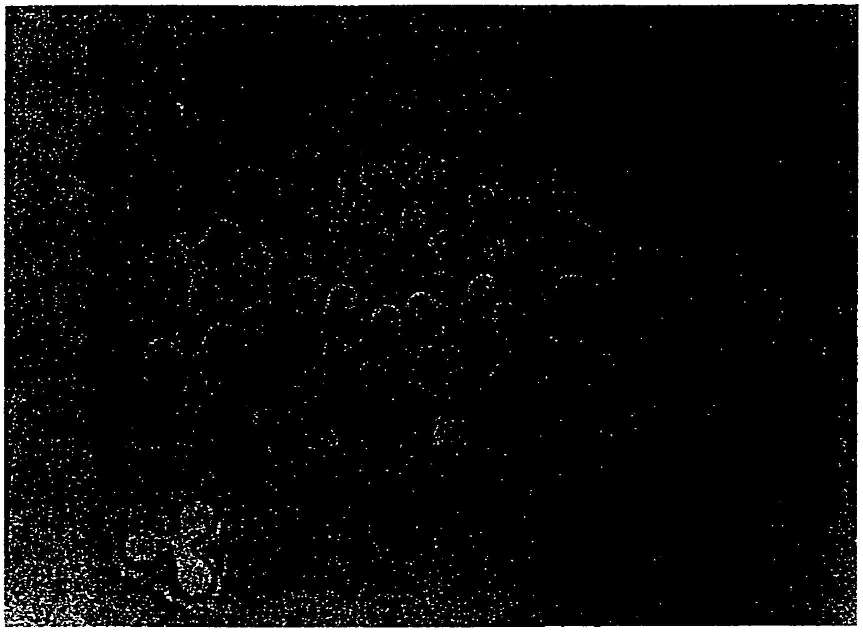


Fig. 5.7.b. Glass fibres of non-circular cross-sections: bilobal (a) and trilobal (b) glass fibres designed to provide more contact area per unit weight between glass fibres and polymer. (Courtesy of Owens-Corning Fiberglas Corporation.)

5.2.2.1. Special fibres and special nozzles

For many years there has been an interest in non-circular fibres to which, more recently, hollow glass fibres have been added.

Non-circular glass fibres impart greater strength and stiffness to composites which may be connected with the greater surface area in contact with the resin. The critical procedure in forming such fibres is rapid cooling as soon as the special shape of fibre has been formed.

For example, fibres of star-shaped cross-section are formed from nozzles of such cross-section and are frozen in this shape by air jets playing upwards from below the bushing [10]. Bilobal or trilobal fibres (fig. 5.7) are formed by placing two or three nozzles respectively in close proximity to one another so that the fibres, on being formed, coalesce and adhere to one another; here again, it is essential to freeze this configuration as quickly as possible as, otherwise, the three fibres will form one substantially circular fibre [11].

However, a more interesting development has been that of hollow fibres, used in composites where weight saving is a prime requirement (fig. 5.8). They are made from bushings fitted with nozzles which each contain an air pipe located centrally

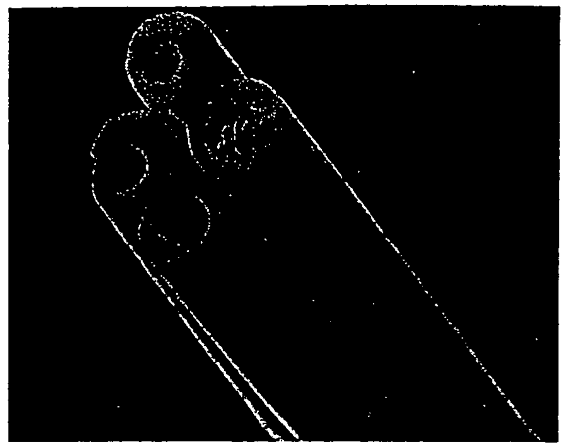


Fig. 5.8. Hollow glass fibres designed to reduce the weight of glass fibre-polymer compos
(Courtesy of Owens-Corning Fiberglas Corporation.)

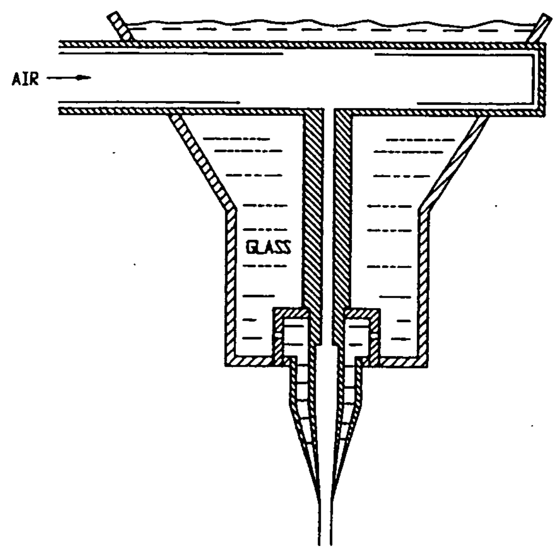


Fig. 5.9. A much-enlarged view of a bushing nozzle designed for the manufacture of hollow g
fibres.

and extending a little distance beyond the annulus of the nozzle (fig. 5.9). A specific example gives the following data [12]:

- Nozzle 3.30 mm bore and 4.76 mm long;
- Tube of 1.57 mm outer diameter, 0.51 mm bore, extending 0.76–1.68 mm beyond end of nozzle; air at 0.038 kg/cm^2 pressure applied to tube;
- Fibre produced: outer diameter 13.0 μm
  inner diameter 8.1 μm

More recent developments have aimed at improving the consistency of hollow bore and overall diameter of the fibre [13]. A specific application is reported to be the use of hollow S-glass fibres/epoxide composites for aircraft parts; such fibres are stated to have one third the weight of the solid S glass fibre, which means that the overall diameter is 1.225 times that of the bore or, in more concrete terms, a hollow fibre of 14 μm would have a wall thickness of 1.3 μm.

Such fibres can be made using either remelt or direct-melt bushings; in both cases, a lot of miniature pipe work has to be added to the normal bushing designed for solid fibres.

5.2.3. The construction of a bushing, its assembly and mounting in a frame

The body of a bushing consists of pieces of platinum alloy sheet of various thicknesses joined together by welding. Welding can be carried out using oxygen-hydrogen flames, helium or argon arc welding, or laser welding. Welding should always be carried out under neutral or slightly oxidising conditions.

The simpler design of bushing is that for direct-melt, as its only functions are to raise the temperature of the glass slightly and to maintain the nozzle plate at a uniform temperature. Figure 5.10 shows a typical direct-melt bushing. Electrical energy for heating is supplied through water-cooled clamps attached to the bushing terminals, one at each end. The contact area between clamp and terminal is either silver or copper; in order to prevent alloying of platinum with the contact metal, the latter must be water-cooled. This water cooling contributes its own cooling effect on the end sections of the bushing itself and adjustment of the position of the contract clamp is therefore often used to modify the temperature of the ends of the nozzle plate.

The thicker triangular sections of the side walls (A in fig. 5.10) are a necessary contribution towards achieving uniform temperature distribution over the orifice plate; this applies to both direct-melt and remelt bushings. The dotted line (D) at the top of the bushing indicates a perforated plate, sometimes called a basket, which assists in the conditioning of the glass and retains any piece of refractory which could have become dislodged. The perforations should therefore be smaller than the bore of the nozzles. With modern refractories and proper handling of melter and forehearth the arrival of refractory stones at a bushing position is a very rare event; when it does occur, the presence of such a piece of refractory 'poisons' the glass flowing past it and makes fibre forming from the zone of the

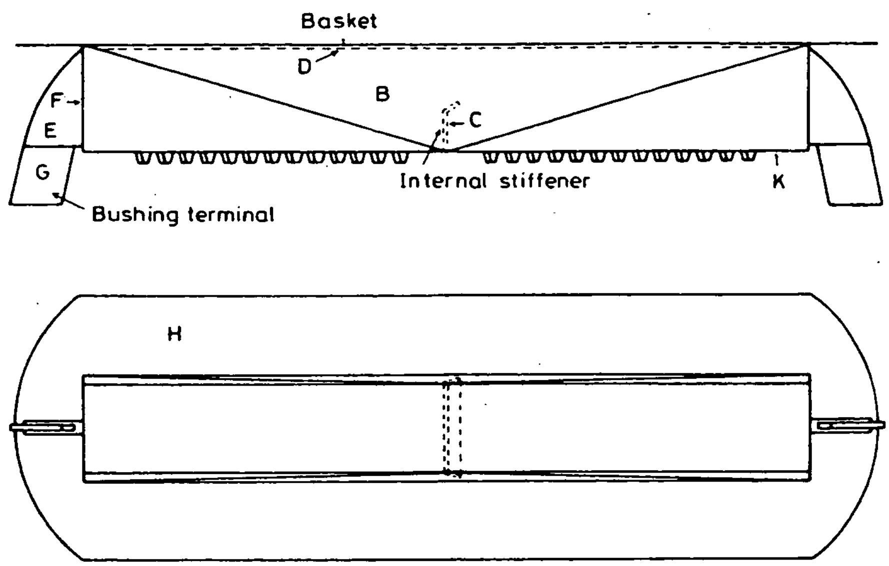


Fig. 5.10. Typical direct-melt bushing. Above, side elevation; below, view from underneath with orifice plate removed. Overall length of orifice plate about 300 mm for a bushing with 400 nozzles. Typical thicknesses of alloy in mm: A = 1.0 to 1.5, B = 0.8 to 1.1, C = 0.75 to 1.0, D = 0.50, E = 5.0 to 7.0, F = 1.75 to 2.25, G = 2.75 to 3.50, H = 0.50, K = 1.0.

nozzle plate immediately below the stone difficult, if not impossible. The bushing would have to be removed from operation, the glass and refractory removed and then be re-installed.

Some manufacturers appear to have separated the perforated plate from the bushing and made it into a separate unit provided with its own sidewall and collars and heated separately like a bushing. The concept of installing this unit separately is to leave it in place when a bushing has to be changed. By providing air cooling through pipes the glass in the upper section can be frozen; the process is restarted by heating after the new bushing has been installed [14]. Of course, should a piece of refractory land on the perforated plate, it would still have to be removed for cleaning, but the fact that these concepts are used, bears witness to the rarity of this event.

A direct-melt bushing is made by starting from the orifice plate and making or installing the nozzles first. The rigidity of the orifice plate can be raised by making this plate 6–8 mm wider than its final width, and bending over the excess 3–4 mm on each side before joining the sides of the bushing to them. This procedure is especially recommended if the nozzle plate is made of dispersion-strengthened sheet as welds nullify its advantages; by moving the welds away from the nozzle

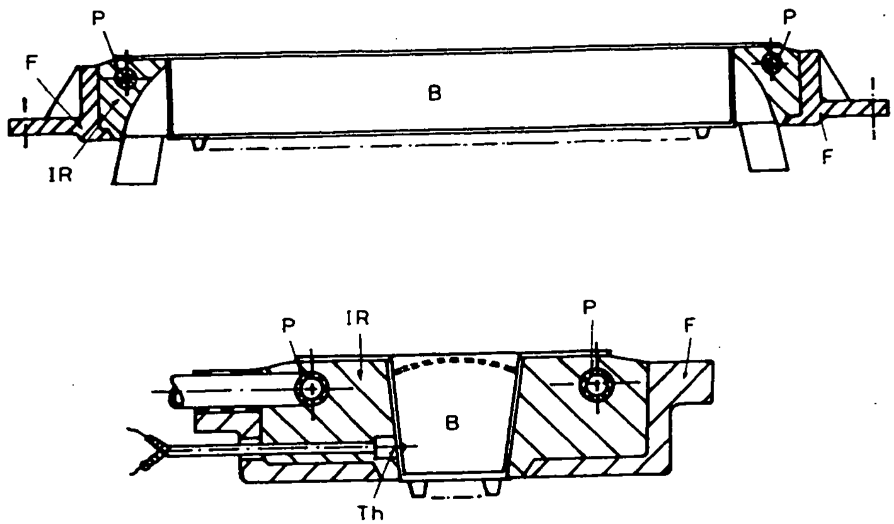


Fig. 5.11. A direct-melt bushing assembled in its frame and surrounded by insulating refractory. Above, side elevation cross-section; below, end elevation cross-section. B is bushing, F bushing frame, IR insulating refractory, P water-cooled pipe, Th thermocouple.

plate the benefits of dispersion-strengthened platinum metal are secured over the whole working width of the nozzle plate.

The sides are made next and welded to the up turned edges of the nozzle plate. This is followed by addition of the end plates, which are slotted to receive the terminals. Pre-manufactured terminals are then inserted into the slots of the end plates and secured by heavy welds both on the inside and the outside of the body of the bushing. Thermocouples are then attached at the centre of the side walls about 10 mm above the nozzle plate by drilling a hole through the sidewall and welding the thermocouple wires into it; usually two couples are installed, the second being a precaution in case the first couple fails. Similarly, any supporting wires needed to support the bushing in its refractory are welded into place by the same technique. Lastly the basket, if used, is welded along the top edge of the bushing, followed by welding on the wide flat collar.

The bushing is then assembled in a frame which, because of its location between busbars of an alternating electric supply, must be non-magnetic and must also be resistant to creep at 400–500°C. Aluminium bronze 5–6 mm thick and of composition (weight %): Ni 5, Al 9.5, Fe 5, Mn 1.5, and Cu the remainder, is satisfactory and can be cast into suitable frames. Insulating refractory is placed between frame and bushing, leaving only the flat collar and basket exposed at the top, the nozzles at the bottom, and the terminals protruding at each end for clamping to the electric supply (fig. 5.11). Further, in order to allow the bushing to expand with respect to

the frame some thin sheets of ceramic insulation are inserted between bushing end plates and refractory.

The bushing in its frame can now be attached to the underside of a forehearth by clamping the frame to it. For ease and repeatability of location, the steelwork of the forehearth often carries two locating pegs and the bushing frame two holes to receive these pegs. The flat collar of platinum metal at the top of the bushing lies flush against the flow block in the base of the forehearth through which the glass will flow into the bushing (see fig. 4.34). This collar acts as a kind of gasket, but since it is not possible to rely on sufficiently good contact to prevent glass leaking out, a water-cooled plastic-covered stainless steel pipe is inserted into the frame immediately under the collar; this freezes any glass flowing between bushing collar and the refractory above it.

With proper handling, the operating life of a bushing is about a year, larger bushings having, perhaps, a slightly shorter life. When a bushing has failed, or its production rate has fallen to an unacceptably low level, it is replaced by a new bushing. The old bushing is then taken out of its frame and the glass removed by melting and/or hydrofluoric acid treatment. The platinum metal can then be recovered by melting and refining, if necessary, then rolling into new sheet. The turn-round losses of platinum metal vary between manufacturers, but, generally speaking, can be assumed to lie between 0.75 and 3% per year of use; this loss becomes one item of the operating costs. The variation in loss is partly accounted for by the fact that the large manufacturers carry out their own recovery of platinum metals and minimise losses by only refining when contamination of the metal is found to have occurred. Smaller manufacturers use specialist companies to recover their platinum metals and supply them with kits of parts for their own assembly or complete bushings: in this case, the specialist company is obliged to refine the metal to a standard which suits all its business.

The direct-melt bushing has been discussed in some detail, although many aspects of its construction, assembly, life, and platinum metal losses also apply to remelt bushings. Remelt bushings can, of course, operate using glass of any more-or-less regular shape, such as long rods, short cylindrical sections of rod, tubing, pieces of sheet, etc. But marbles are the most common material used as they are easily made and handled. Apart from the orifice plate, remelt bushings therefore differ among themselves mainly in the design of the feed openings at the top of the bushing.

The construction of a remelt bushing is similar to that of a direct-melt bushing except that the basket, being in this case of real 'basket'-shape, has to be attached not only at the top of the side walls but also to the end plates; finally the previously assembled bushing lid with its feed holes, etc. is welded into place.

As in the case of direct-melt bushings, remelt bushings are mounted in a suitable frame of aluminium-bronze – in this case usually in two parts which are bolted together – and supported in this frame in suitable insulating refractory. During the assembly the thermocouple wires in their insulating glass fibre sleeving are led to the outside of the bushing frame, usually appearing at one of the longer vertical surfaces of the frame and about 50 mm above the nozzle plate.

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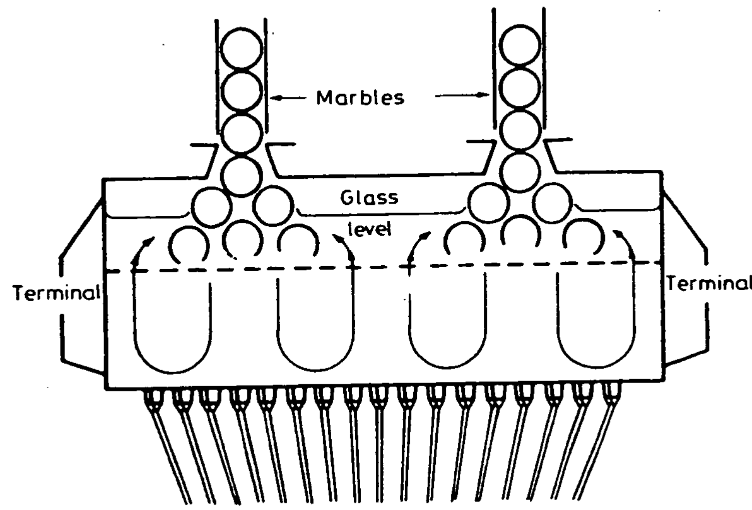

Fig. 5.12. Schematic of a remelt bushing fed with marbles showing the convection currents set up as a result of cold glass melting in the upper part of the bushing.

Frame sections near the nozzles and terminals often distort in use; however, they can be straightened when the bushing is removed at the end of its life, and the frame re-used.

The insulating refractory must support a bushing throughout its operating life which is, on the average, about 1 year. It must therefore stand up to a temperature of 1250°C without shrinkage. Also, since it is in contact with platinum metals, its composition must exclude metal oxide impurities such as iron oxides, which should be less than 1% calculated as Fe_2O_3. Insulating materials of this type are available in two forms, either as pieces which can easily be cut by saw or similar tools to give a shape that can be made to fit closely around a bushing, or in the form of a cement powder which, when wetted with water, can be cast around the bushing. In order to make sure that all air escapes from the cement, it is best to cast it around the bushing on a vibrating table. When using insulating refractory pieces these should be joined with insulating cement both between bushing and refractory and between the pieces of refractory themselves.

The design and operation of remelt bushings is more complicated than that of direct-melt bushings due to the fact that it has to melt cold glass in addition to conditioning it to a uniform temperature for fibre forming and passing it to the nozzle plate. The cold glass melting at the top of this bushing sets up considerable convection currents in the bushing which make their own contribution to the temperature distribution of the nozzle plate (see fig. 5.12).

The necessity to allocate energy for the two functions calls for consideration of

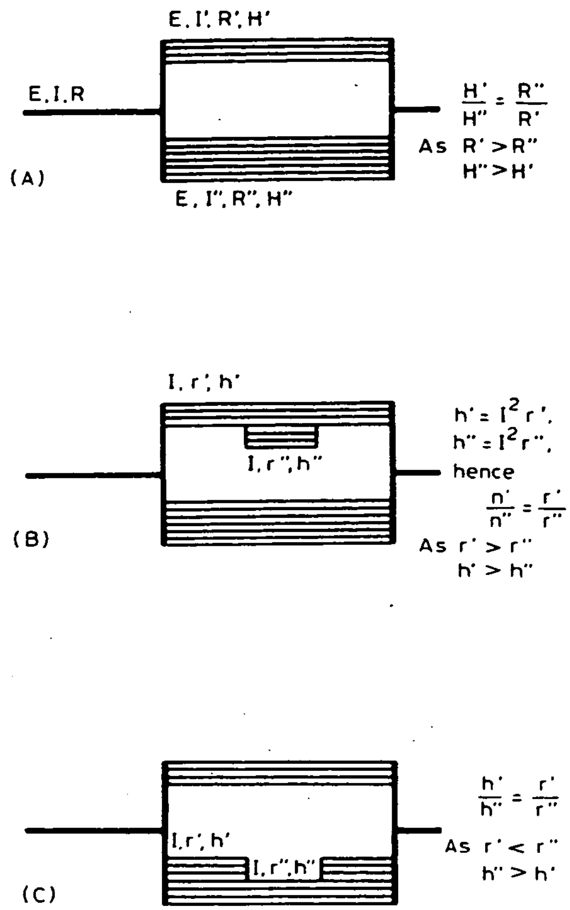

Fig. 5.13. Basic principles of heat distribution in bushings as affected by the thickness of alloy sheet used. *A*, *B* and *C* represent resistances in parallel of alloy sheets of different thicknesses. *H* or *h* represent the heat evolved. *R* or *r* the electrical resistances. *E* the voltages and *I* the currents.

the distribution of electrical energy and its conversion into heat in the walls of the bushing. (Although alternating current is used for heating bushings, the discussion which follows is based on direct current since it is simpler and provides the same answer.) Figure 5.13 shows the alternatives. In (a) a comparison is made between a thick and a thin section connected in parallel. It is clear that the ratio of the heat evolved is proportional to the cross-sectional areas, i.e. the thicker piece will be the hotter. In (b) a thick piece of metal is inserted into a conductor of thinner section. Since the current is the same for the whole assembly, and the heat evolved is given by $H = I^2R$, it is clear that, since the resistance of the thicker section is less, the thicker metal will be cooler. In (c) the converse applies: a piece of thinner section is inserted into a line of thicker cross-section. Since the resistance is increased, the thinner section will be hotter.

For bushings these simple concepts can only be used as a basic guide to enable changes to be made in a certain direction. Since the metal sheets of different thicknesses constituting a bushing are welded together along edges often running from one terminal to the other, some lateral flow of current is inevitable. This factor affects the temperature distribution in a way that is not easy to predict.

The design of a remelt bushing is therefore rather complex and is, in practice, evolved from experience rather than designed based on theoretical concepts. Figure 5.14 gives an example of a simple design. In order to prevent unmelted glass from reaching the nozzles, this type of bushing must have a basket at the top to retain the glass and assist in melting it. To assist melting in this area, the thickness of the end plates is sometimes increased towards the top of the bushing. There are two schools of thought covering the broad distribution of sheet thicknesses. One school has the thickest sheet near the nozzles (e.g. $C = 1.25$, $B = 1.0$, $D = 0.75$, E, F and $I = 0.5$ mm), the other school thickens components E and F, e.g. to 1.0 and 0.75 mm respectively, and sometimes also reduces D in order to create comparatively more energy at the top of the bushing. For big remelt bushings, e.g. of 800 nozzles, three feed holes have been tried, as well as placing the terminals horizontally in order to get good temperature distribution across the width of the bushing. In some cases, a premelter heated separately has been used to separate the melting from the conditioning functions. Possibilities are unlimited, and experimental costs high. Hence the move towards direct-melt plants wherever they can be applied and whenever they are more economic to operate.

The current position is that fine fibres of 6 μm or under are more economically manufactured by the remelt process. Here the number of nozzles in a bushing usually does not exceed 800, and it is easier to use remelt bushings for sheer convenience and flexibility of operation.

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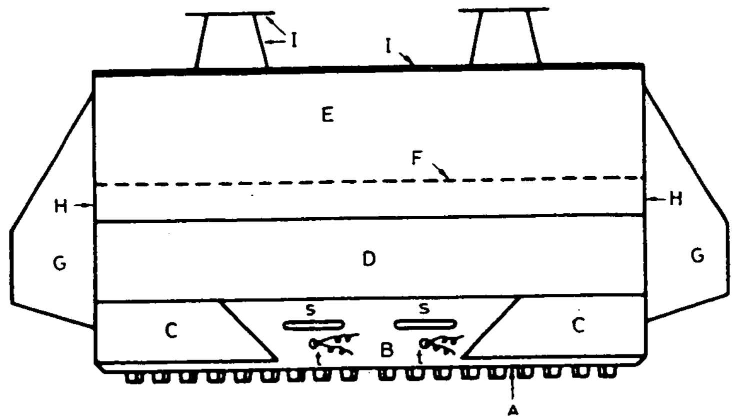
5.2.4. The design of larger bushings

Economic and competitive pressures have forced the glass fibre industry to maintain a constant drive to raise productivity and to reduce costs. One aspect of this drive is to aim to produce the maximum amount of fibre from a given bushing position.



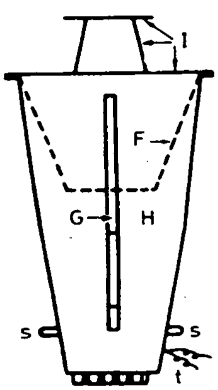


Fig. 5.14. Typical remelt bushing of 400 nozzles for melting marbles (approximately 300 mm long, excluding terminals) with typical thicknesses of alloy.

i.e. the bushing and its associated equipment. Since a bushing cannot operate in isolation, a related aspect of this drive has been the development of new winders capable of winding two or more cakes at a time, or direct roving winders which wind rovings direct from the bushing; the latter have not only raised productivity but have also made it possible to eliminate a whole production stage.

In this development, the design of bushings of greatly increased throughputs has been crucial. Since the direct-roving winder is limited to a linear speed of about 1000 m/min, the bushing must be provided with many more nozzles to compensate for the reduction in winding speed. The problem has been eased by increasing the diameter of the filaments produced step by step in line with what the customer could accept. Filament diameters of 17–24 μm for direct-wound rovings are now

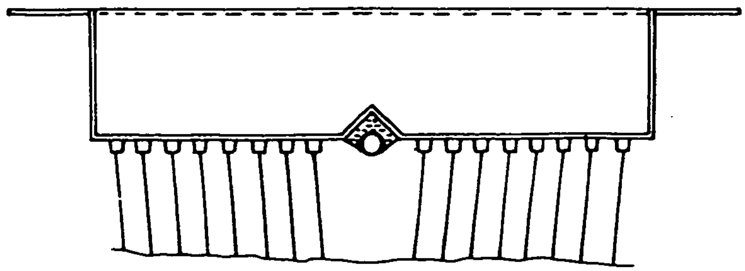


Fig. 5.15. External support for large bushings consisting of a water-cooled stainless steel pipe located centrally and longitudinally under the orifice plate with refractory cement between pipe and nozzle plate.

common. Bushings with over 4000 nozzles are now in operation, and it must be assumed that bushings of 6000 nozzles are not far away, if not already in use. Such bushings, when producing filament of 16 μm, for example, can make rovings (for weaving and winding) of the normal 2400 tex at a rate of over 100 kg/h.

The larger throughput bushings present major design and operational problems:

(1) the need to maintain the very large nozzle plate at a uniform temperature; and
(2) the need to minimise the distortion of the nozzle plate at the operating temperature and under the head of glass above the nozzle plate.

The first point has been covered by suitable variation in the metal thickness of the various parts of the bushing sometimes coupled to major design changes such as placing terminals horizontally. In addition, the inlet of the bushings and the outlet of the forehearth has been arranged so that the glass flows into the bushing in lamellar flow and, as near as possible, at the temperature required for fibre forming. Thus the energy input into the bushing is minimised, as is the problem of temperature variation of the nozzle plate itself.

The creep of bushings at elevated temperatures and under the loads normally existing cannot be eliminated. It is possible to use stiffer or dispersion-strengthened platinum alloys in whole or in part (see Section 5.2.1), but mechanical stiffening partly within the bushing and partly outside the bushing has been necessary. Figure 5.15 shows such an external support; it consists of a stainless steel pipe, water-cooled, located longitudinally along the centre line of the bushing with refractory cement or pieces of refractory located between pipe and nozzle plate.

Internal stiffeners are really beams running across the width of the bushing and welded to the orifice plate and the side walls similar to the one shown in fig. 5.10. An alternative method, used occasionally, is to weld beams above the orifice plate from one sidewall to the opposite one, then attach wires to these beams and weld them to the orifice plate (fig. 5.16).

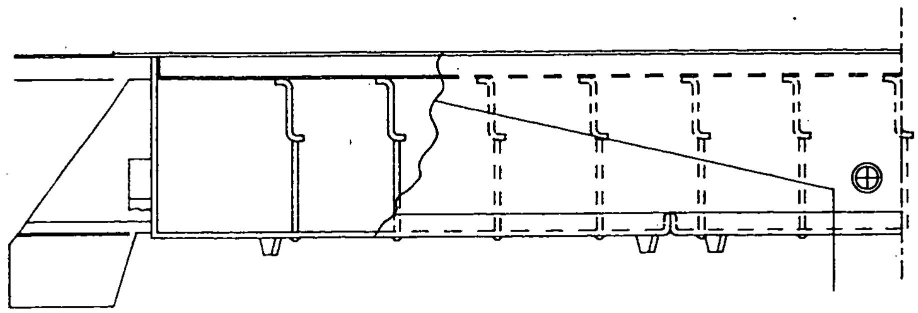


Fig. 5.16. Alternative method of supporting a large orifice plate. Wires attached to stiffeners extending across the width of the bushing are welded through the orifice plate.

Table 5.2
Typical data of weights, filament diameter, throughput, attenuation rate and life of bushings. (The bushings can be assumed to be of 10Rh·Pt composition.)

Nozzles/ bushing	Bushing weight ~kg	Fil. dia. μm	Total tex[a] g/km	Thru- put kg/h	Atten. rate[b] km/min	Typical life days
Remelt:						
200	3.6–4.2	5–6	10–14	3–4	5.0–4.8	250
400	4.1–5.0	5–6	20–28	5–6	4.1–3.6	250
Direct melt:						
400	1.4–1.6	5–9	20–68	6–19	5.0–4.7	250–350
800	2.1–2.3	6–13	55–270	10–32	3.0–2.0	300–400
1200	2.9–3.3	9–11	195–300	30–40	2.5–2.2	300–350
1600	3.5–4.1	9–13	250–540	45–60	3.0–1.9	300–400
2000	4.4–5.1	11–16	480–1020	50–70	1.7–1.1	250–325
4000	7.1–7.8	16–24	2030–4600	80–110	0.6–0.4	220–300

[a] The total tex is equivalent to the tex of all filaments together irrespective of whether they are divided into more than one cake or roving or whether they are further subdivided into split strands.
[b] The higher attenuation rates apply to the manufacture of fibres of lower filament diameter and lower tex.

Overall, these developments have enabled a whole range of bushings to become available. Table 5.2 gives some examples including some remelt bushings.

Bushings can be tailored for particular applications. For direct chopped strands, for example, there may be a call for a mixture of filament diameters. Thus, if a mixture of 9 μm and 16 μm filaments are required to be made from a bushing of 2000 nozzles, half the nozzles can be made of 1.70 mm bore, the other of 1.22 mm: such a bushing would produce about 44 kg/h of chopped strands [15].

5.2.5. Bushings without nozzles - the 'C' process

Compared to earlier hopes, only brief mention need now be made of a design of bushing which was derived from the spinnerets used in the manufacture of organic fibres such as nylon. While pressurisation of the glass supply led to engineering problems which could not be overcome, it did lead to a design of bushing in which the orifice plate was only provided with holes from which the glass filaments would be attenuated. Figure 5.17 shows such a bushing; in this case, the orifice plate has been stiffened by providing a supporting box structure as shown.

The menisci necessary for filament formation are stabilised by providing air cooling upwards against the orifice plate from sets of air jets located under the orifice plate and slightly to one side to permit the filaments to pass. Exit air velocities of 30–120 m/s from the air nozzles have been reported [16].

This process, when operating and forming fibres, is very productive when making filaments of 18 μm and over. The problem which has led to this process being progressively abandoned is the time necessary for restarting the production process following a filament break and, as a consequence, the flooding of the orifice plate. The cleaning operation is tedious and long winded and require 30 min or more to return the bushing into operation; it also calls for an operator of special skills and the patience of Job. Overall, most manufacturers have found that once the high productivity when operating was offset by time losses due to filament breaks and the subsequent cleaning process, the overall efficiency was reduced to a level where bushings based on the traditional orifice plate with nozzles proved to be more economical.

However, there is at least one bushing design using holes which is specially designed to overcome these problems. Figure 5.18 shows a design in which flooding cannot extend to more than a limited number of holes; thus, if flooding occurs, it can only comprise the holes on one 'island', and it is likely that glass from a hole where the filament has broken will simply transfer itself to an adjacent filament which will, of course become coarser, but no coarser than can result from the glass flowing out of the number of holes on one island [17]. As soon as this occurs, the very fact that fibre forming continues to be drawn is believed to ensure that the coarse filament will itself separate into the number of filaments which equals the number of holes on the one island. This 'flexibility' can also be used to manufacture both coarse and finer fibres from the same bushing simply by reducing winding speeds.

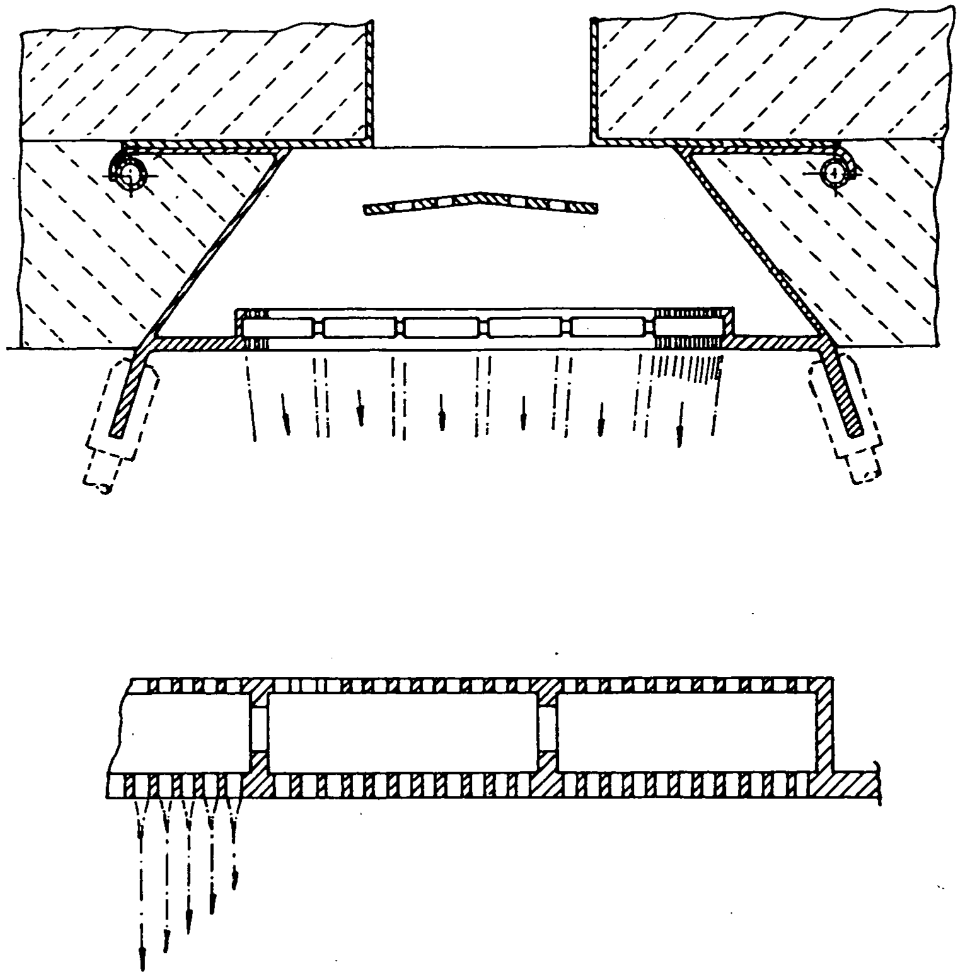
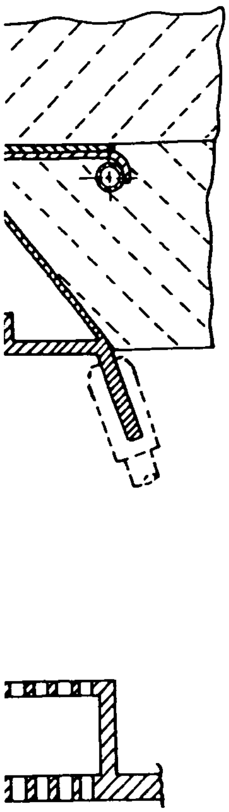


Fig. 5.17. A typical bushing according to the 'C-process'. Above, a general view: below, an enlarged view of part of the orifice section showing a perforated plate above the orifice plate proper and connecting members between the two designed to stiffen the structure and, thereby, reduce distortion of the orifice plate.



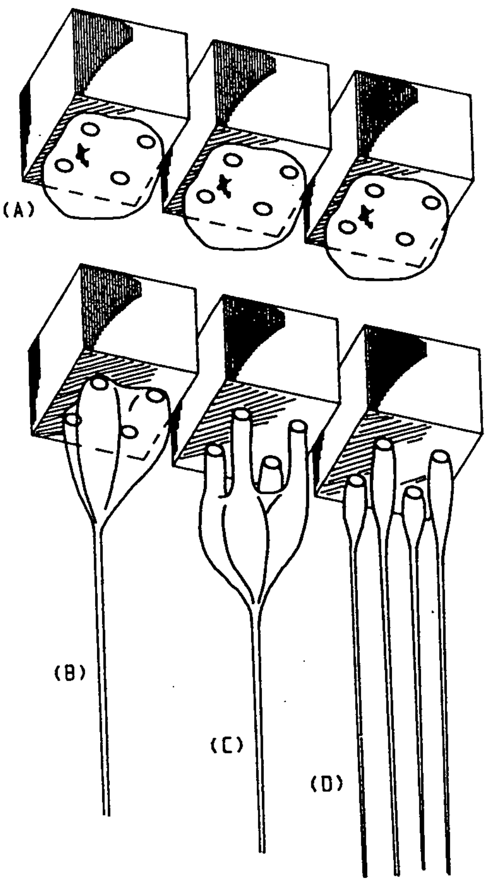


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Fig. 5.18. An example of the development of the 'C-process' bushing to overcome the problem of large-scale flooding of the orifice plate in the event of a filament break during attenuation. The effect of a filament break will be confined to one island, resulting in one coarse fibre continuing to be drawn which, as soon as the excess glass has been pulled off the orifice plate, will revert to a multiplicity of filaments being drawn (sequence B to D).

Although the use of bushings with holes instead of nozzles has ultimately not been successful, advantage can be taken of experience gained. Thus it has been claimed that fibre forming from large bushings of 4000 nozzles can be stabilised by locating a pipe horizontally and lengthwise below the centre of the bushing and blowing air from this pipe into both sides of fibres downwards at an angle of 60°; such a bushing is claimed to produce about 84 kg/h of fibre [18].

5.2.6. *Nozzle shields and the stability of the fibre forming process*

Reference has already been made to the need for achieving a stable meniscus for the efficient conversion of liquid glass into fibre. From the point of view of the glass composition itself, a point that has become increasingly important as new compositions are being developed is the fact that, the lower the liquidus temperature of the glass the more stable it is against devitrification, i.e. against the formation of crystals which would seriously interfere with fibre production (see also Section 4.2). Bearing in mind that, in the course of the fibre forming process, the temperature of the glass changes rapidly while it passes through the nozzle on its way to attenuation, and that devitrification must be avoided in order to maintain an efficient fibre forming process, it follows that, the greater the difference between the temperature of the glass during fibre forming (T_F) and the liquidus temperature (T_L), the lower the risk of crystallisation occurring. In practice, a minimum difference of 50°C has been stated as necessary, with a preferred difference of 100°C. For E glass the difference is 140°C; for some of the alkali-resistant glasses used for reinforcing cements, the differences are often less than 140°C.

The stability of the meniscus is also a function of the 'draw-down ratio', i.e. the ratio of the diameter of the meniscus as it leaves the nozzle, to the diameter of the fibre being formed. The larger this ratio, the less stable is the fibre forming process.

For a given glass composition there is a narrow range of temperature within which the balancing forces of surface tension and viscosity make for a stable meniscus and permit the continuous formation of glass fibre. If the viscosity is too high, i.e. the temperature too low, the tension necessary for fibre forming can exceed the tensile strength of the fibre just formed, which will then break. If the viscosity is too low, the meniscus becomes unstable, a fact that can be observed by the 'pumping' phenomenon just below the meniscus, indicating an intermittent passing of fibre of greatly increased diameter. At some moment enough glass will arrive in the meniscus to temporarily raise the temperature of the glass to a value at which surface tension will become the dominant factor; the fibre will then break at the meniscus. The range of viscosity in which a glass should be held for fibre forming is given by $\log \eta = 2.5$ to 3 poise, or is between 600 and 1000 poise.

All these factors come together to be optimised in the use of nozzle shields (also called fins), probably one of the most important inventions in the technology of fibre forming from glasses [19, 20]. Historically, the problem which they were designed to overcome was the fact that, if more than four rows of staggered nozzles were used in a bushing, fibre formation in the centre rows became unstable; the reason

was that in the centre of such a configuration, the heat radiated by menisci and nozzles prevented the glass being cooled to within the viscosity range required for stable fibre formation. Nozzle shields are simply a device for absorbing energy from nozzles and glass and, by placing these between rows of nozzles, would stabilise fibre forming from bushings of any number of nozzles or rows of nozzles.

For maximum production from a given bushing, the objective is to pass the maximum amount of glass through each nozzle, keep the draw-down ratio to a minimum, and bring the glass to within the range of viscosity which gives stability of fibre formation.

Nozzle shields are heat sinks which absorb energy and conduct it away through water cooling systems. They enable the temperature of the glass in the bushing to be kept higher, thus increasing the throughput of the nozzle, they enable the draw-down ratio to be kept lower, and they cool the glass more rapidly thus holding the glass of the meniscus within the desired viscosity range. They are of two kinds:

(1) The most common nozzle shields are constructed of flat strips of metal about 15 mm wide and 1.5 mm thick, and joined at one end to a manifold through which water flows as a coolant. They are placed transversely across the width of the bushing (see fig. 5.19): for very large bushings, nozzle shields are placed opposite one another, one from each side. Since thermal conductivity is important, the shields were originally made from silver: however, this proved too dangerous as even the shortest accidental contact between silver fin and the platinum alloy of a bushing would cause fatal damage to the latter. The next-best metal, copper, is corroded too easily; thus nickel-clad copper has become the standard for these strips.
Small bushings of not more than 200 nozzles can use one set of nozzle shields; for bushings of 400 nozzles two sets are used. For larger bushings the number of sets is increased in line with the design of the bushing, i.e. in line with the presence of gaps in the groups of nozzles caused by stiffeners, etc. Obviously the water cooling circuits for all sets of nozzle shields of a bushing should run in parallel.
Nozzle shields are usually adjusted by unclamping, then moving the assembly. This method is reasonably satisfactory for small bushings, but is difficult to carry out with bushings of over 1200 nozzles. For these, a new method allows the assembly to remain clamped while horizontal and vertical adjustments can be made by means of adjustment screws.

(2) The alternative nozzle shields consist of flattened metal pipes through which water flows (fig. 5.20). The pipes should have a wall thickness of about 0.25 mm, be flattened to 3 × 10 mm, and should be connected at each end to a manifold linking them to a water-cooling system. Alternatively, the flattened pipes can be held securely separately and be connected by means of flexible pipes to the water circuit. These type of shields are best constructed of 5% rhodium–palladium alloy with the manifolds in stainless steel. The shields are installed so that their top edge is in line with, or just below, the nozzle outlets. Vertical

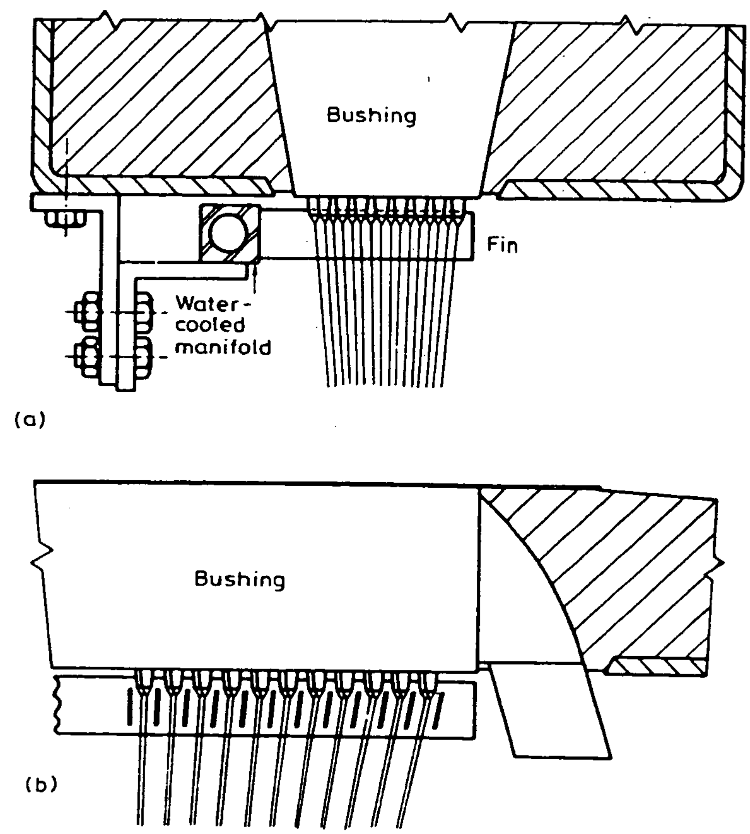

Fig. 5.19. Transverse nozzle shields constructed from metal strips welded into a water-cooled manifold. In (b) the strips located towards the terminal end of the bushing have been bent to take account of the angle at which the fibres are being drawn.

adjustment of the assembly must be provided to enable resetting in line with possible warping of the orifice plate as it ages.

The advantage of the use of shields of flattened metal pipes is that they can be installed with the bushing and, accidents apart, have the same life as the bushing. Dust and dirt which adheres to them after a while can be cleaned in situ by use of a fine water jet and a small stainless steel wire hook (note that electric power to the bushing must be switched off during this operation). The disadvantage of this type of nozzle shield is that the bushing has to be lengthened to leave space for the manifolds located between the last nozzles and the terminals, and that the gaps left between rows of nozzles for the cooling pipes have to be larger than those for flat metal strips. In all, equivalent bushings

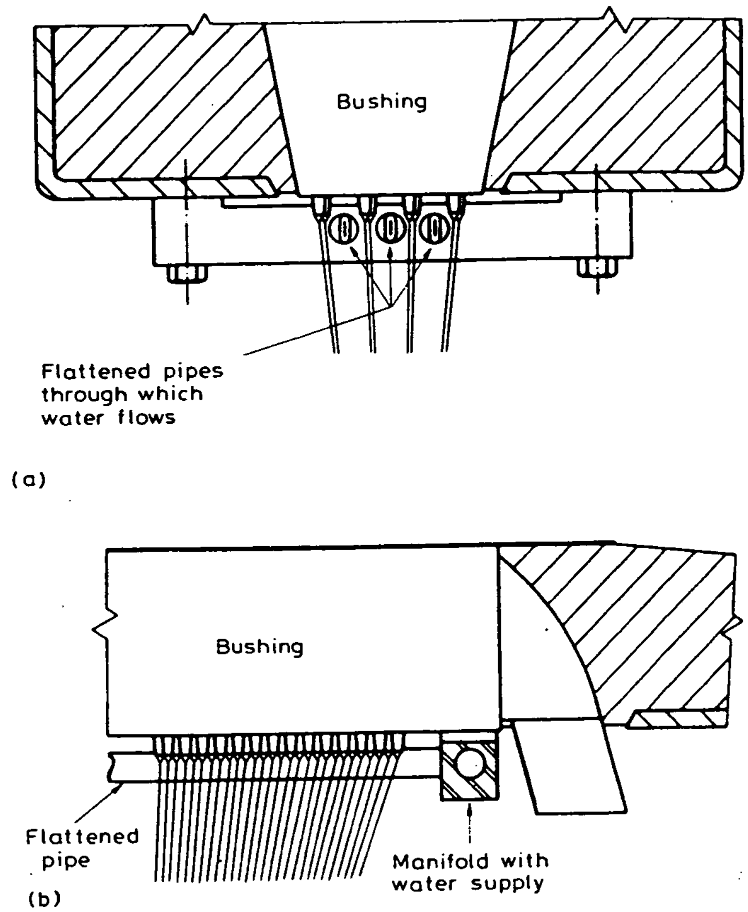

Fig. 5.20. Longitudinal nozzle shields constructed from water-cooled flattened metal pipes welded at each end into a manifold which also provides the water supply. This arrangement avoids the risk of filaments touching the shields but also calls for a larger orifice plate and, therefore, a higher investment in platinum metals.

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The advantage of the shields of metal strips is that they are easily installed and adjusted and can operate with bushings of lower platinum metal weight than would be the case if longitudinal shields were used. Their disadvantage is that they have to be removed for cleaning every few weeks, and new strips have to be inserted every 6–12 weeks; it therefore calls for a additional maintenance effort. However, in experienced hands and with proper discipline these work very well and are the most common type of shield now in use.

5.3. Bushings, heating and associated services, temperature control, and their start-up and operation

Bushings are heated electrically by connecting them across the low voltage windings of a step-down transformer. Bushing temperature is controlled automatically via thermocouples attached to the bushing and linked to a bushing controller. Bushing controllers are now available which incorporate a variety of programmes, such as enabling the bushing temperature to be increased with time, controlling the heating up schedule of a bushing, etc.

5.3.1. Bushing electrics

Figure 5.21 is a diagram of the electrics. A 380 or 440 V single-phase supply passes through a voltage regulator which acts as the power controller to the bushing. Power passes from the voltage regulator through an approximately 100 : 1 step-down transformer and from there, via heavy connections, to the bushing. Bushings typically operate at 3–6 V and several thousand amperes, depending on the size of the bushing.

Voltage regulators now used are silicon-controlled rectifier a.c. power controllers (SCR). The SCR operates as a 'gate' and, depending on a signal, will only let part of the alternating wave cycle pass through.

The SCR is small and comparatively light-weight and can be housed together with the temperature controllers in the clean atmosphere of the control room; alternatively, since modern devices accept an ambient atmosphere of 50°C, they can be installed close to the transformer to reduce power cables. The SCR can have a rating much higher than is required for a particular bushing and have its maximum power output limited by a (misnamed) current limiter. An overriding control is also available to set the minimum power level which the rectifier will pass. Both this control and the current limit control are of importance when temperature ramps are employed (see below).

Transformers can be of the air-cooled or water-cooled variety; the latter have the advantage of taking up less space and being able, if this is important, to be mounted closer to a bushing. Transformers can also be installed with considerable

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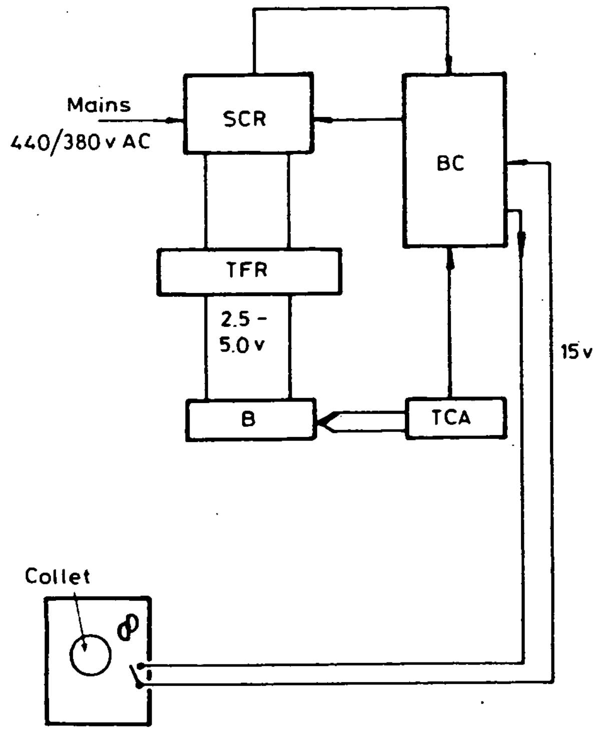

Fig. 5.21. Bushing electrics showing an SCR power controller receiving a signal voltage (0-80 V, or 0-5 V respectively) from the bushing controller. All control functions are part of the bushing controller (BC). B is the bushing, from where thermocouples are connected through short compensating cables to a thermocouple amplifier (TCA). Any ramp functions act directly on the bushing controller by adjusting its set point. The bushing controller is linked to the collet motor so that, whenever winding is interrupted, the ramp function is returned to zero. TRF is the bushing transformer.

overcapacity; in this case it is advantageous to have a range of voltage tappings available from, say, 3 to 6 V in steps of $\frac{1}{2}$ V. The connections are then made to the bushing at the lowest tappings which give enough power to operate successfully.

The installed power requirements of remelt bushings vary considerably with size; they are also a function of the cross-section and length of busbars between transformer and bushing. The following is a rough guideline for bushings at the throughputs (i.e. glass melting rates) stated:

200	nozzles	15–20 kW	9–10 kg/h	throughput
400	"	25–30 kW	14–18 kg/h	"
800	"	35–45 kW	22–28 kg/h	"

Table 5.3
Estimated energy balance for power consumed by two remelt bushing.

Bushing (throughput of glass)	400 nozzles (17 kg/h)	200 nozzles (10 kg/h)
Purpose:		
Used to melt glass	4.9 kW	2.9 kW
Rigid and flexible connections	2.5	1.6
Water-cooling of contacts	3.5	3.0
Orifice plate radiation	3.0	2.0
Feed hole losses	0.5	0.5
Loss into refractories	2.0	1.8
Nozzle shields	1.7	1.3
Total	18.1	13.1

Of this energy only a small proportion is in fact used to heat the glass from room temperature to the temperature needed for fibre forming. An estimated energy balance from the transformer onwards is given in Table 5.3.

Direct-melt bushings operate at considerably less power since little energy is needed to raise the glass to the fibre forming temperature, the bushing is much smaller, and the top surface, being in contact with the underside of the forehearth, suffers little heat loss. Hence the running load of a 400-nozzle direct-melt bushing would be of the order of 7–8 kW. Running loads of larger bushings are:

800	nozzle	9–11 kW	25–30 kg/h	throughput
1600	"	14–16 kW	41–48 kg/h	"
2000	"	15–17 kW	50–60 kg/h	"
4000	"	19–21 kW	73–80 kg/h	"

However, the installed power must be greater to enable the bushing to be started, remembering also that in the course of changing bushings during the period of a furnace campaign (see Section 5.3.5), the glass in the connecting refractory slot has to be frozen and has to be heated up again to get the glass to flow and restart the fibre forming process. A transformer of 25 kW should be adequate for all direct-melt bushings up to 800 nozzles: above this, the available power must be raised.

The connections between transformer and bushings are important both in an electrical and mechanical sense. Electrically, the shorter they are, and the larger their cross-section, the less power is wasted in them. Mechanically, the connections to the bushing must be flexible, both to allow for thermal expansion and to permit fine adjustments to be made which affect temperature distribution of the orifice plate near its ends.

Figure 5.22 shows a typical arrangement for a marble bushing. The rigid bars are of electrolytic tough pitch copper, in this case 100–150×6–9 mm in cross-section,

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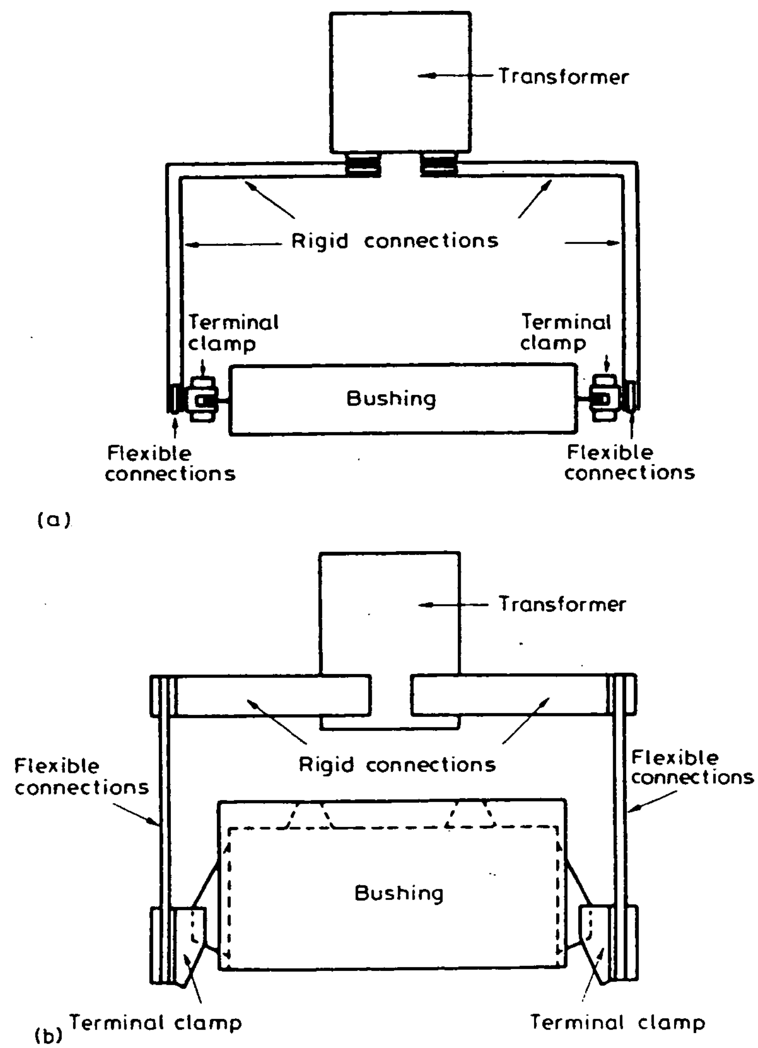

Fig. 5.22. Connections between a remelt bushing and its transformer.

and two bars from each terminal. These are followed by a set of flexible copper connections, each 75–100 mm wide ×0.25 mm thick, the number being equivalent to the cross-section of a pair of rigid connection from the transformer. The connection between the bundle of flexible copper strips and the bushing terminals is via a special terminal clamp.

For direct-melt bushings, access to the bushing is very restricted; with careful design it is possible to get the transformer just alongside the forehearth and at such a height that, for bushings placed parallel to the length dimension of the forehearth, it is possible to have the flexible connections as the only conductor between transformer and terminal clamps. If the bushing is placed across the forehearth, at least one pair of rigid connections is needed as is shown in fig. 5.23.

Typical clamps for remelt and direct-melt bushings are shown in fig. 5.24. They are water-cooled. In order to ensure good contact between clamp and bushing terminal all clamps, unless new, should have their contact surfaces re-machined before installation. Some fibre manufacturers use silver inserts to act as contact surfaces since they resist corrosion better than copper; other operate successfully without inserts. This difference in approach is probably related to the corrosiveness of the atmosphere surrounding the bushing and will be discussed further in Section 5.7.

During operation, the clamps occasionally require adjustment inwards or outwards in order to adjust the heat pattern of the orifice plate, especially towards the ends. This involves disconnecting the electric power to the bushing, loosening of the clamp bolts, sliding the contact to a different position with respect to the bushing terminal, and re-tightening the clamp bolts, and reconnecting electric power. This hit-and-miss method is surprisingly crude bearing in mind the delicate nature of platinum metals and the critical setting required for efficient operation of the bushing. Even in expert hands, instances of terminals being broken off cannot always be avoided. Attempts to use a liquid contact in which the cold end of the bushing terminal rests in a cup of indium–gallium–tin alloy have not been successful [21]. In any case, the risk of over-stressing the terminal can be reduced by the use of torque-limiting spanners when tightening the contact clamps.

5.3.2. *Temperature control and temperature ramps*

There are a number of instrument manufacturers who market excellent and compact equipment for controlling the temperature of bushings. Accuracies of 0.5°C are claimed. Thermocouples of bushings are connected via compensating cable in an earthed conductor to the temperature controller. In large plants, where the runs of compensating cable would be extensive, hermetically sealed temperature transmitters can be located near the bushing and near the SCR; these devices provide cold junction compensation, and isolate and amplify the thermocouple signal such that it can be transmitted to the controller as a high voltage or current loop signal. Control signals as normally used are 0–5 V, 0–10 V and 4.2 mA and cause the SCR to vary the power passing to the transformer and, from there, to the bushing.

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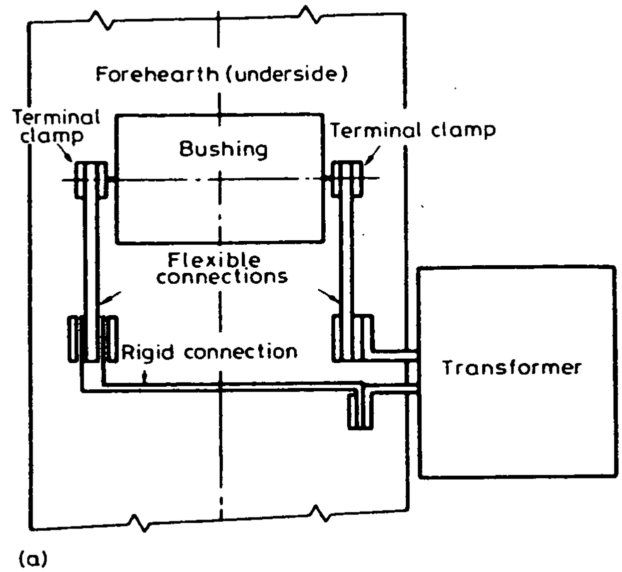

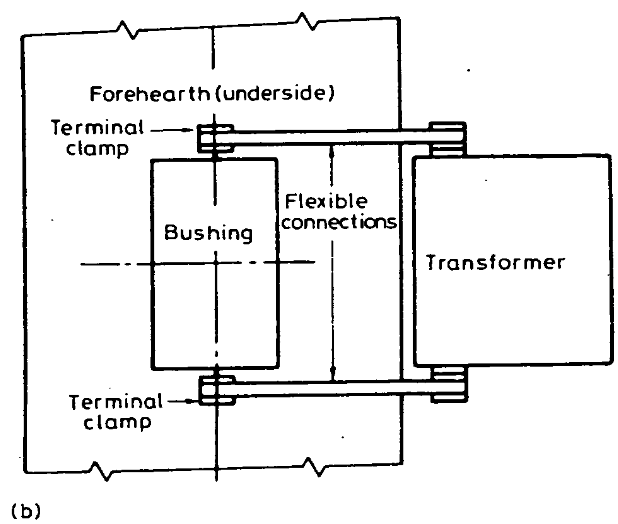

Fig. 5.23. Connections between direct-melt bushings and transformers. The design depends on the positioning of the bushing relative to the forehearth.

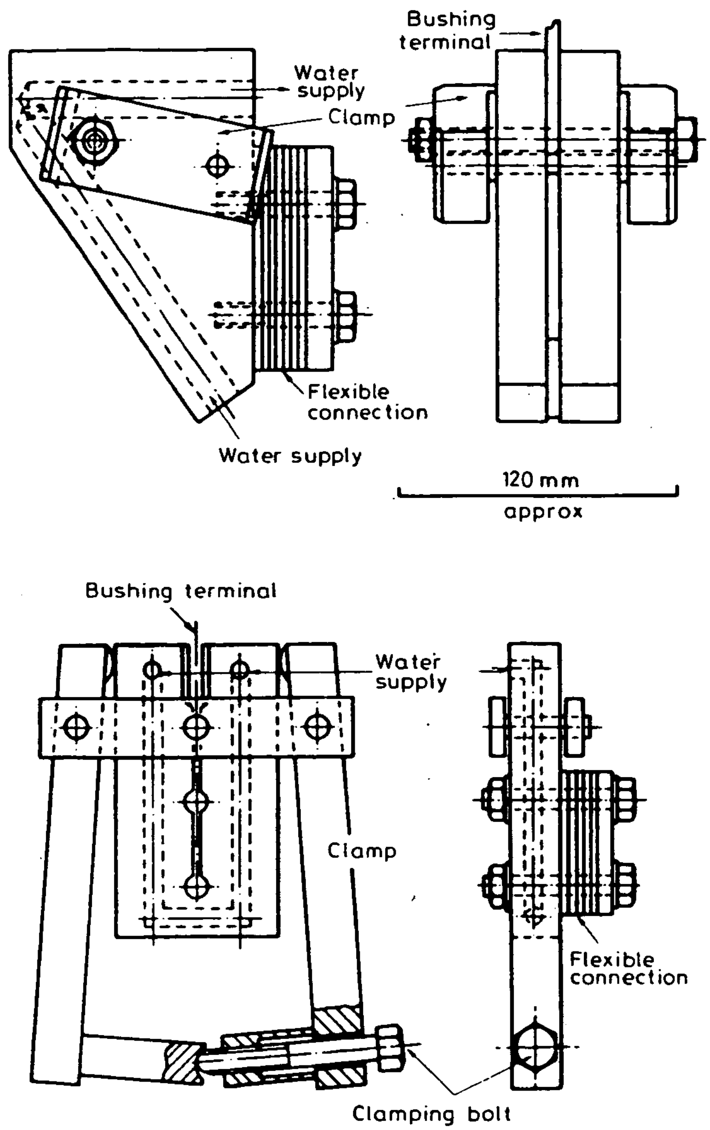

Fig. 5.24. Clamps for connection of bushing terminals to the flexible connections from the transformer. Above, for a remelt bushing; below, for a direct-melt bushing.

Modern control equipment comprises a set of modules which can provide the following functions:

(1) Temperature gradient control during the heat-up of a bushing from cold to its operating temperature. It can be achieved by limiting the output of the controller and thereby the SCR current dependent on the measured temperature.
(2) A temperature ramp set at a predetermined rate to slowly raise the temperature of a bushing in compensation for the increase in linear drawing speed which arises as the layer of fibre builds up on a collet of a winder rotating a constant rpm.
(3) A temperature 'jump ramp' or setpoint depression to provide a rapid limited temperature increase during acceleration of the collet at a start of a winding cycle; this acceleration takes place for about 20 s.
(4) A thermocouple failure warning and current limiter to prevent a bushing from overheating under this condition. If two thermocouples are provided and both are connected to the controller, an automatic switch-over to the stand-by thermocouple can be performed. Alternatively, or for close temperature control at the centre of the bushing, the two thermocouple signals can be averaged to provide the control measurement.
(5) A manual override to enable the bushing to be controlled manually after thermocouple failure or for any other reason.
(6) A bias which fixes the minimum level of power always going to the bushing.

Temperature ramps are designed to alter the temperature setting of the controller according to a predetermined time schedule. Their purpose is to increase productivity and maintain quality by holding the tex of the fibre constant while the linear rate of attenuation increases. It is a well-known fact that the maximum temperature at which a bushing can operate, i.e. at which the menisci just remain stable, can be about 10–20°C above the maximum temperature at which fibre attenuation can be started, quite apart from the often emphatically stated wishes of operators to have the glass colder for easier handling when starting fibre forming operations. Expressed differently, once fibre is being drawn from a bushing at a temperature which was the maximum possible for starting, this temperature can then be increased by a limited amount without adversely affecting the stability of the fibre attenuation process.

Anticipating Section 5.6, it is also clear that a fibre winder operating with a collet at constant rpm will make progressively finer fibre as the thickness of fibre builds up. For example, a collet of 200 mm diameter will wind fibre 25% finer after a layer of 25 mm thickness has been deposited: for a collet of 300 mm diameter, which is now the most common in use, the increase is 17%. As this change in tex is clearly undesirable for a large range of glass fibre products, a temperature ramp can be used to eliminate or minimise this effect. Rates of temperature increase of between 0.3–0.5°C/min have been used. The programme is set as required by trial and error and is linked to automatic switching so that the ramp comes into operation with each start of fibre winding, i.e. when the traverse comes into operation, and returns

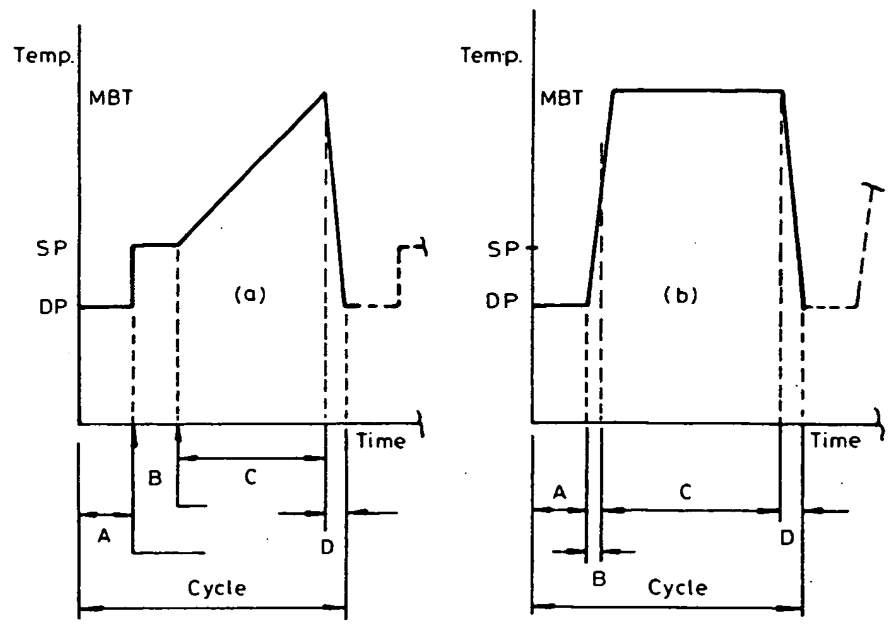

Fig. 5.25. Alternative bushing temperature/time programmes covering the winding of a single cake. In (a) the programme consists of a temperature ramp designed to compensate for the increase in linear drawing speed as the cakes builds up on a collet operating at constant rpm. In (b) the programme is set to give maximum fibre output. The greater area under the curve in (b) when compared to (a) is a measure of the extra fibre produced. (Legend: MBT = maximum bushing temperature; SP = setpoint temperature; DP = set point depression; A = doffing; B = collet acceleration; C = useful production; D = collet deceleration.) The DP is used to reduce the setpoint temperature by, say, 10°C while an operator attends to the bushing; the bushing returns to the setpoint temperature as soon as the winder is started.

to its starting temperature when the winder is stopped for doffing. Figure 5.25(a) shows the temperature/time effect.

The alternative and now preferred way of ensuring constancy of fibre tex throughout the winding cycle of a cake is by programming the rpm of the collet so that the linear speed stays constant while the layer of fibre builds up.

The maximum fibre output will be achieved if the bushing is operating at the maximum temperature for the maximum proportion of the available time. In this case, the ramp is programmed to increase bushing temperature to its maximum in minimum time – this can be arranged to take about 15 s – and the collet is set to give constant linear speed, i.e. gradually decreasing rpm. Figure 5.25(b) shows the temperature/time effect; the larger area under the curve between (B) and (a) is a measure of the additional output of the fibre if this 'jump ramp' programme is followed.

Bushing controllers and associated equipment should all be housed together in an air-conditioned slightly pressurised control room which, in the case of a direct-melt plant, can be the same control room as is used for the operation of the furnace. If desired, the equipment can also be distributed into three locations: (i) the field equipment (transformer, SCR, and temperature transmitters) near the bushing, (ii) the controllers in a central control room associated with these bushings and related operations, such as the furnace, and (iii) a VDU system in an overall plant control room.

5.3.3. Power and control connections to the bushing, start-up and operation

The life of a bushing, when properly used, is about 10 months to one year, depending on its size. In order to achieve this with the minimum of interruptions it is necessary to be critical in respect of quality and conditions of items connected to the bushing. Terminal clamps, if not new, should be as good as new when brought into use with a new bushing. The flexible connections should be clean and, if there is a tendency for them to be corroded by the atmosphere surrounding the bushing, they should be coated with conducting grease.

Whether for direct-melt or for remelt bushings the flexible connections carrying the clamps should be attached to the rigid bar connections from the transformer in such a way that, when also attached to the bushing through the clamps, the clamps have to be moved inwards towards the bushing, i.e. together they pull slightly on the terminals. Also, the clamps should slide freely over the bushing terminals so that no lateral force is applied to them. Since the operational position of the clamp cannot be established until after the bushing has been heated up, an initial position covering two-thirds of the terminal can generally be recommended. The clamps are tightened onto the terminals using, preferably, torque spanners.

Most bushings are fitted with two thermocouples, one for use and one for spare, or for testing, or both are used for averaging the temperature readings. Both should be connected to the controller either totally via compensating cables or through temperature transmitters. In order to avoid signal interference, compensating cables should be run in earthed conduit.

To start a bushing, the controls can be set on manual and power increased in small steps. The rise in temperature can be read by reading the temperature on the controller. Small frequent increases are to be preferred to larger less frequent ones. A bushing heat-up from cold to fibre forming temperature should take about $2\text{–}2\frac{1}{2}$ h. When the heat-up is completed the temperature reading on the controller is adjusted until it indicates zero $\pm 3°C$ deviation; the controls can then be switched to automatic.

Alternatively, use can be made of the heating-up programme included with some controllers. These controllers are provided with multiple output limits which, if set correctly, will allow the controller to be set to 'automatic' with the normal operating set-point at 'cold'. The heating up schedule is divided into temperature sections of break points and, at each break point, the current demand to the SCR

will not increase beyond a pre-set level until the bushing temperature has reached this break point. This procedure can also be used for protecting the bushing after a power failure.

It is a basic principle of fibre manufacture that the bushing controls all other factors. The temperature of the bushing is raised until, when drawing fibre, the menisci under the nozzles become unstable. By then reducing the set-point temperature by 10°C, a good initial operating temperature is obtained. Since it takes some hours for the whole bushing assembly to attain thermal equilibrium, it is best to let the bushing operate at the initial temperature setting until strand tex has stabilised.

At this stage it will be noticed whether the orifice plate has an even temperature. If not, one or both clamps may need adjustment: switch off the power, loosen the clamp bolts, move the clamps by 1–2 mm, tighten the clamp and switch power back on. In this fashion, crude though it is, the zones of the orifice plate nearest the clamp are affected. Moving a clamp closer to the bushing cools this area, and vice versa.

If a gradual temperature ramps is to be used, the following factors will have to be monitored and adjusted on an ad hoc basis until fibre of the required and constant tex is made:

(1) Base temperature.
(2) Temperature increase per minute.
(3) Fibre tex at the beginning of the cake.
(4) Fibre tex at the end of the cake.
(5) Attenuation rate at the start of winding the cake in rpm.
(6) Attenuation rate at the end of winding the cake in rpm (if different from (5)).

If a jump ramp is used, the base temperature can be decided solely to suit the convenience of the operator; this is followed by establishing the maximum temperature increase that will give stable fibre attenuation. Once this has been found the starting rpm can be fixed in relation to the tex of the fibre, followed by programming the collet ramp so that the collet rpm decreases with increasing layer of fibre deposited on it while the fibre tex stays constant, i.e. the linear speed stays constant.

In some cases, the use of the gradual and the jump ramps are combined, the former to control the tex of fibre made and the latter to assist the operator in starting the fibre forming operation, hence the alternative name of 'set-point depression'. The use of ramps implies frequent sudden temperature changes. To minimise power fluctuations and thermal shock effects with consequent adverse effects on bushing life, controllers now operate on integral action during the jump ramp which means that the increase temperature demand during the jump ramp is a natural exponential with time-adjustable constants. Alternatively, use can made of the 'current limit' and 'bias' by which both maximum and minimum power available to the bushing are set. For example, a current limit giving a power input at 10–15% above

the normal running power, and a bias which fixes minimum power at 30% below normal have been know to operate well.

A very useful tool to study, check, and set ramps is a portable temperature recorder covering the range 1150–1350°C over a scale of 100–200 mm, and with a chart movement of about 20 mm/min; this can be connected to the control thermocouple (or the spare) while adjustments are made and gives a visual record of each temperature cycle.

5.3.4. The behaviour of bushings as they age

At the temperature of operation platinum–rhodium alloys undergo changes in crystal structure which influence brittleness of the metal and its strength. In addition, some metal is lost where exposed to the atmosphere, the bushing becomes misshapen, and the perforated sheet, originally shaped as a flat trough, takes on a catenary shape; the side walls buckle, the orifice plate sags in both directions. In some case physical adjustments must be made to nozzle shields to keep to approximately the optimum distance, and the range of the temperature ramps must eventually be reduced or eliminated. The temperature distribution of the orifice plate may change and call for adjustment of clamp positions; in some fatal cases, there is, in the end no adjustment left. These are changes that can occur in the normal course of the life of a bushing, and lead to progressively lower production rates.

When to replace a bushing is a question which must be decided in relation to the loss of production occurring with age, the cost of replacing the bushing, and the advantages to be gained by replacing it (a bushing of improved design or performance may by then be available). Usually bushings fail in some fatal manner, e.g. poor temperature distribution of the orifice plate, impossible to correct, or a glass leak. Sometimes there are accidents such as contamination of the bushing by non-platinum metal which lead to its destruction, damaging of nozzles during nozzle shield adjustment, or excessive force being used to tighten clamps leading to glass leakage near the terminals. In these cases the bushing must be changed; the corollary of this statement is that there must always be some spare bushings available for installation.

In most cases, however, first failures are of a minor nature and such bushings can be repaired and put back into operation (see Section 5.3.6).

5.3.5. The replacement of bushings

The replacement of a remelt bushing is straightforward and does not require any comment. The replacement of a direct-melt bushing, however, while not difficult in itself, is a hot job in a confined space and calls for some special tools and systematic working of a small team of specialists so that the work is completed in the shortest possible time. Among the special tools are platform steps of the correct height to reach the bushing (not needed if the bushing is at head height), a water lance,

asbestos gloves, etc. Spare ancillary components should be on site so that, should any be found defective, they can be changed at the same time.

The problem of removing a bushing from a direct-melt forehearth is the need to prevent glass running out from the flow block in the floor of the forehearth while there is no bushing in position. This is done by temporarily freezing the glass in the flow block. The procedure in its essentials is quite simple:

(1) Switch off all power to the bushing and all other equipment associated with this position. Disconnect terminal clamps and remove nozzle shields (if of the transverse type), etc.
(2) Accelerate cooling of bushing by periodically spraying a jet of water onto the bushing frame and the nozzles.
(3) Remove bushing retaining clamps. Continue spraying periodically until the bushing is cold, i.e. below red heat. A few taps with a hammer and chisel between bushing frame and underside of forehearth usually suffices to free the bushing. Disconnect water to bushing cooling coil.
(4) As bushing is removed, spray water onto glass in flow block in floor of forehearth. Repeat with bursts of water spray whenever the glass heats up.
(5) Remove any lumps of glass from the exposed side of the flow block using a small chisel and hammer or, better, a pneumatically-powered chisel. Take care not to damage the refractory.
(6) As soon as the refractory is clean, place the new bushing in position, secure with retaining clamps, connect to terminal clamps, and connect water supply to cooling coil. Switch on power at half normal running power and gradually increase, aiming to have bushing in operation within 2 h.
(7) Other equipment is reconnected and/or maintained within the heating-up period. Adjustments of orifice plate heat pattern, optimum operating temperature, collet rpm, etc. follow in the usual way.

5.3.6. The repair and construction of bushings in the plant

Large glass fibre manufacturers carry out their own metal recovery and, presumably, make their own sets of parts before assembly. Most of the smaller manufacturers assemble bushings from 'kits of parts' supplied by the platinum manufacturers. Whether to engage in this activity is not only a question of relative economics since other factors come into play which are not so easy to quantify.

The Alloy Room, as it is frequently known and in which this work is done, consists of at least three sections plus an optional extra:

(1) A section for removing an old bushing from its frame and refractory (and storing this refractory for recovery of platinum metals), and for setting new or repaired bushings in new refractory in its frame.
(2) A section for the removal of glass from bushings by crushing and chipping, followed by a final clean by sandblasting in a glove box or cleaning in hydrofluoric acid. If hydrofluoric acid is used, special precautions must be taken as this

material is highly poisonous and inhalation and contact with the human body must be avoided. Therefore the 'HF' treatment must be carried out in a separate room which must be designed to resist attack by hydrofluoric acid and must be provided with controlled ventilation so that all vapour is drawn away from the operator. For safety, the operator must also be provided with protective clothing and breathing apparatus and, in case of spillage or accident, must have immediate access to a step-on shower.

(3) A section for the construction of bushings where damaged bushings are repaired or new bushings assembled from kits of parts using, in the main, argon arc or laser welding techniques.
(4) A section for melting recycled metal, rolling it and cutting to the thickness and shapes of the parts required. Since the composition of the alloy may need adjustment before casting, a rapid method of analysis of platinum alloys needs to be on site.

The advantages of the glass fibre manufacturer carrying out the recovery of platinum metal himself is that platinum metal losses can be held to very low figures, usually under 1% per year of the metal in use. However, for the smaller manufacturer, the possession of only the first three sections also brings significant advantages:

(a) complete accounts can be kept of the metal used and lost for every bushing or other platinum metal item (e.g. those in the furnace);
(b) accidental damage to a bushing and minor failures can often be repaired on site in a shorter time than is possible if they are returned to the platinum manufacturer;
(c) it is easier and quicker to control bushing development work, especially since such development, in most cases, proceeds in steps of small changes;
(d) by being able to assemble bushings from kits of parts, the inventory of platinum metals can be smaller than if a large range of different bushings have to be stored in case of requirement for use; and
(e) by examining and recording the location and types of fault which make bushings inoperable, information leading to improvements in bushing design and construction is more readily available.

5.4. Fibre size applicators

Before the individual filaments being drawn from a bushing are gathered and consolidated into a strand, or a multiplicity of strands, they are coated with a fibre size. These fibre sizes are of two types:

(1) starch-oil sizes usually applied to fibres intended for weaving into fine fabrics or for braiding or for insulating electric conductors; and
(2) coupling agent plus film former sizes applied to fibres intended for the direct reinforcement of plastics and rubber; this can also include fabrics.